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CLIMATE CHANGE MITIGATION BY BIOLOGICAL CARBON SEQUESTRATION OF DIFFERENT MAIZE HYBRIDES

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UBLAŽAVANJE KLIMATSKIH PROMJENA BIOLOŠKOM SEKVESTRACIJOM UGLJIKA RAZLIČITIH HIBRIDA KUKURUZA

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ABSTRACT

The year 2024 is the warmest year since records began and the first calendar year in which the global average temperature exceeded 1.5°C above pre-industrial levels. Therefore, methods to reduce greenhouse gas emissions and increase their sinks are being intensively investigated. The aim of this research is to determine the potential of different maize hybrids to mitigate climate change through biological carbon sequestration. In this research, biomass yield and biomass carbon content are determined for four different maize hybrids grown in continental Croatia during the 2021 harvest. The investigations showed that the carbon content in the root, stubble, stalk, cob, husk and grain of the different maize hybrids on average amounted 1.21 t ha-1, 0.4 t ha-1, 5.42 t ha-1, 0.91 t ha-1, 0.47 t ha-1 and 4.33 t ha-1, respectively. There is no statistically significant difference between the studied hybrids in the carbon content in cob and grain, while statistically significant differences were found for the carbon content in root, stubble, stem and husk. The results of the study suggest that by selecting maize hybrids that sequester more carbon and through good biomass management, more atmospheric carbon can be removed from the atmosphere and soil fertility can be increased.

SAŽETAK

Najtoplija godina od kada postoje mjerenja i prva godina kada je globalna prosječna temperatura zraka bila iznad 1.5°C viša u odnosu na predindustrijsko razdoblje je 2024. Stoga, metode smanjenja emisija i povećanja ponora stakleničkih plinova se sve više istražuju. Cilj ovoga rada je utvrditi za različite hibride kukuruza njihov potencijal ublažavanja klimatskih promjena putem biološke sekvestracije ugljika. Prinos biomase i sadržaj ugljika u biomasi, su utvrđeni za četiri različita hibrida kukuruza uzgojena u kontinentalnoj Hrvatskoj tijekom žetve 2021. godine. Sadržaj ugljika u korijenu, strništu, stabljici, klipu, oklasku i zrnu različitih hibrida kukuruza u prosjeku redom iznosi 1,21 t ha^{-1}, 0,4 t ha^{-1}, 5,42 t ha^{-1}, 0,91 t ha^{-1}, 0,47 t ha^{-1} i 4,33 t ha^{-1}. Nisu utvrđene statistički značajne razlike između istraživanih hibrida kukuruza za sadržaj ugljika u klipu i zrnu, dok su statistički značajne razlike utvrđene za sadržaj ugljika u korijenu, strništu, stabljici i oklasku. Rezultati pokazuju da odabirom hibrida kukuruza koji vežu više ugljika i dobrim gospodarenjem biomasom se može ukloniti više ugljika iz atmosfere i povećati plodnost tla.

INTRODUCTION

Periodic climate change, global warming and cooling, are natural climatological cycles of climate variability in the Earth's atmosphere that change at different intervals. Since the industrial revolution, however, climate change has been dominated by human influences that exceed the limits of natural variability *(Karl and Trenberth, 2003).* According to the IPCC (2001) report on climate change, the concentration of carbon dioxide (CO_2) has increased by 31%, of methane (CH_4) by 151% and of nitrous oxide (N_2O) by 17% since the beginning of the industrial revolution up to the year 2000. It was predicted that if anthropogenic greenhouse gas emissions continue to be emitted the atmosphere at this rate, it will be possible that the predicted, previously unrecorded increase in average air temperature of 1.1 to 5.8 °C will be reached by the end of the century *(Tokgöz, 2010).* Unfortunatelly, the 2024 is confirmed by the Copernicus Climate Change Service (2025) to be the warmest year on record globally, and the first calendar year that the average global temperature exceeded 1.5°C above its pre-industrial level. Therefore, methods to reduce

greenhouse gass emissions and increase their sinks are being intensively investigated. The most important greenhouse gas is considered to be CO_2, which in Croatia has the largest contribution with 71.7 % to the total GHGs emission in 2022 excluding LULUCF sector (NIR 2024, 2025).

Carbon circulates in relatively short periods between the atmosphere, the biosphere and the pedosphere. Biological carbon sequestration represents the uptake of atmospheric CO2 in the process of photosynthesis and storage in plant biomass. In agriculture, depending on how the agricultural biomass is managed, some of the biomass is incorporated into the soil after harvesting, storing atmospheric carbon in the soil pool. This not only helps to reduce atmospheric CO_2 levels, but also improves soil health, leading to higher yields, nutrient levels and other agroecological benefits. The storage of atmospheric carbon in the plant/soil pools is complex and depends on many factors, such as crop type and its variety, biomass management, agrotechnical measures, etc. Different crops and their varieties with their morphological and physiological predispositions have a direct effect on carbon sequestration and C input into the plant/soil pool.

Therefore, the aim of this study is to determine the carbon content and its distribution within the plant parts of old and new Croatian maize hybrids.

MATERIALS AND METHODS

Location

A study was conducted during the 2021 growing season at experimental field near Osijek city, continental Croatia (φ = 45°31′56.47″ N, λ = 18°44′16.07″ E; 90 m a.s.l). The size of each experimental plot of the individual maize hybrids was 150 m2 (15 m x 10 m) in three replicates (Figure 1).

Fig. 1 - Experimental field in continental Croatia

Climate

According to Bilandžija and Martinčić (2021), the average air temperature at experimental field during the vegetation season is 18.6 °C and the annual average is 11.7 °C (Table 1).

The average seasonal air temperature of spring is 12.1 °C, of summer 21.7 °C, of fall 11.6 °C and of winter 1.5 °C.

Table 1

Average air temperature (°C) at experimental field during period 1991. – 2018.

	spring	summer	autumn	winter	vegetation	annual
1991. – 2018.						
av	12,1	21,7	11,6	1,5	18,6	11, 7
sd	1,0	1,0	1,0	1,6	0,9	0,8
max	13,7	23,8	13,6	5,0	20,1	12,9
min	10,4	20,1	9,6	-1,5	17,2	10,2

** spring (3.-5.month), summer (6.-8. month), autumn (9.-11. month), winter (12.-2. month), vegetation season (4.-9. month), annual (1-12 month), av – average, sd - standard deviation, max – maximum, min – minimum. (source: Bilandžija and Martinčić, 2021)*

The average precipitation amount of the period 1991–2018 during the growing season is 390 mm and annualy 707 mm with the highest recorded precipitation amount in June (80.7 mm) *(Bilandžija and Martinčić, 2021)* (Table 2).

Table 2

Average precipitation amount (mm) at experimental field during period 1991. – 2018.

	spring	summer	autumn	winter	vegetation	annual
1991. – 2018.						
av	167	207	196	142	390	707
sd	55	91	70	60	149	161
c_v	0,33	0,44	0,36	0,43	0,38	0,23
P_{max}	282	519	318	295	699	1038
P_{min}	35	78	45	1	155	317

** spring (3.-5.month), summer (6.-8. month), autumn (9.-11. month), winter (12.-2. month), vegetation season (4.-9. month), annual (1-12 month), av – average, sd - standard deviation, cv - variation coefficient, P_{max} – maximum, P_{min} – minimum. (source: Bilandžija and Martinčić, 2021)*

Soil properties

The soil at the experimental site has a silty-loam texture with a content of 2.33% sand, 56% silt, and 41.67% clay. The water holding capacity is 37.7%, air holding capacity is 10.2%, soil porosity is 47.8%, and bulk density is 1.39 g cm−3. The soil pHKCl is 7.24, and the soil contains 2.3% humus, 0.11% total nitrogen, 1.25% total carbon, 0.06% total sulfur, 17.9 mg of P_2O_5, and 15.5 mg of K_2O per 100 g of soil.

Maize hybrides

The experiment includes 4 different maize hybrids (Zea mays L.) bred by the Agricultural Institute Osijek. Two new hybrids Rudolfov 60 and Kulak and two old hybrids OSSK 515 and OSSK 596 were studied. Maize hybrides properties are presented in table 3 and more on maize hybrides can be found in cataloque of Agricultural Institute Osijek *(AIO, 2020)*.

Table 3

Properties of maize hybrides

	RUDOLFOV	KULAK	OS 596	OS 515
Purpose	dry grain production, ear harvesting, silage production		ear harvesting, silage production	silage production
Kernel type	dent-type kernel			
Number of rows of kernels	16 – 18		14 – 16	16 – 18
Recommended plant density	68 000 – 71 000 germinable seeds/ha	71 000 – 75 000 germinable seeds/ha	65 000 – 68 000 germinable seeds/ha	68 000 – 71 000 germinable seeds/ha
Sowing distance	20 – 21 cm apart	19 – 20 cm apart	21 – 22 cm apart	20 – 21 cm apart

Source: Agricultural Institute Osijek (2020)

Biomass sampling

Sampling of the below-ground (root) and above-ground (stubble, stalk, cob, husk and grain) plant parts of the maize hybrids was carried out in three replicates. The biomass was sampled by destructive method from 1 m^2 of the experimental plot (Figure 2).

Fig. 2 - Field biomass sampling

After field sampling of biomass at the experimental field, the samples were delivered on the same day to the Faculty of Agriculture University of Zagreb where the below-ground biomass was cleaned of soil particles and the above-ground biomass was fragmented (Figure 3) and weighed.

After weighing, subsamples were taken from each plant part of the maize and prepared for the laboratory determination of the carbon content in the biomass.

Fig. 3 - Fragmentation of above-ground biomass

Determination of carbon content in biomass

Total carbon content in above- and belowground biomass was determined simultaneously bye dry combustion method. Biomass samples were dried in an oven *(Nueve, FN 120, Ankara , Turkey)* at 105 °C to a constant weight, weighed (Sartorius CP 64; d = 0.1 mg, Göttingen, Germany), and analyzed using the Vario Macro CHNS analyzer (Elementar, Langenselbold, Germany). Total biomass carbon content was determined according to the HRN ISO 10694 2004 protocol. To obtain carbon yields in t/ha, the dry matter yield of each biomass fraction is multiplied by the carbon concentrations of each fraction.

Statistical analysis

The statistical analysis was performed with the statistical software SAS 9.*1 (SAS Inst. Inc., 2002–2004, Cary, NC, USA)*. The variability between the investigated maize hybrides was analyzed by analysis of variance (ANOVA) and, if necessary, tested with the Fisher post-hoc t-test. The significance threshold for all analyzes was 5%. The quality management system (QM) complies with good laboratory practice and includes internal and external quality controls (QC).

RESULTS AND DISCUSSION

The average carbon contents of all maize hybrides studied are 1.21 t ha^{-1} for root, 0.4 t ha^{-1} for stubble, 5.42 t ha^{-1} for stalk, 0.91 t ha^{-1} for cob, 0.47 t ha^{-1} for husk and 4.33 t ha^{-1} for grain. The descriptive statistic for carbon content average values of all maize hybrids by the individual plant parts of the biomass are presented in Table 4.

Table 4

Average carbon content of all maize hybrides (t ha^{-1}) in individual plant parts

	Root		Stubble		Stalk		Cob		Husk		Grain	
	av	sd	av	sd	av	sd	av	sd	avr	sd	av	sd
average	1.21	0.33	0.4	0.06	5.42	1.17	0,91	0,1	0,47	0,12	4,33	0,53
min	0.85		0.31		3.88		0.75		0.28		3.61	
max	1.81		0.5		7.85		1.06		0.77		5.41	

*av – average, sd - standard deviation, max – maximum, min – minimum

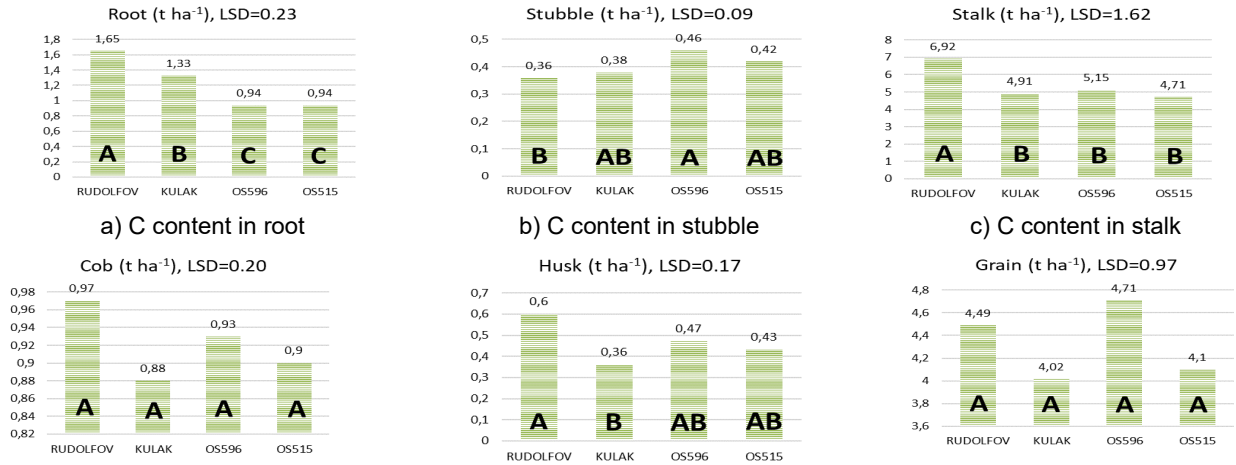
Figure 4 presents carbon content in individual plant parts for each maize hybrid studied. The The dry matter yield of roots ranges from 2.57 to 4.43 t ha^{-1} and percentage of carbon in roots between 34.8 to 38.19 % depending on maize hybride. The carbon content in the roots ranges from 0.94 to 1.65 t ha^{-1}. The statistical analyses determined that the carbon content in the root (Figure 4a) of the Rudolfov hybrid is significantly higher than that of the other hybrids studied.

The Kulak hybrid contains a statistically significantly higher amount of carbon in the roots compared to the OS 596 and OS 515 hybrids, and significantly lower compared to Rudolfov. There is no statistically significant difference in the carbon content in the roots between the OS 596 and OS 515 hybrids.

The dry matter yield of stubble ranges from 0.97 to 1.33 t ha^{-1} and percentage of carbon in stubble between 34.28 to 38.19 % depending on maize hybride. The carbon content in the stubble ranges from 0.36 to 0.46 t ha^{-1}. The carbon content in the stubble (Figure 4b) differs significantly only between the Rudolfov

hybrid and OS 596, which has the highest amount of stored carbon in the stubble, while no significant difference was found between the other hybrids studied. The dry matter yield of stalk ranges from 10.40 to 14.40 t ha^{-1} and percentage of carbon between 45.34 to 48.03 % depending on maize hybride. The carbon content in the stalk (Figure 4c) ranges from 4.71 to 6.92 t ha^{-1}. The carbon content in the stalk of the Rudolfov hybrid is significantly higher than that of the other maize hybrids studied, between which no statistically significant difference was found. The dry matter yield of cob ranges from 1.74 to 2.00 t ha-1 and percentage of carbon between 48.44 to 50.38 % depending on maize hybride. The carbon content in the cob ranges from 0.88 to 0.97 t ha^{-1} (Figure 4d). No statistically significant difference in the amount of carbon in the cob was found between the maize hybrids studied. The dry matter yield of husk ranges from 0.77 to 1.23 t ha^{-1} and percentage of carbon between 44.50 to 48.82 % depending on maize hybride The carbon content in the husk ranges from 0.36 to 0.60 t ha^{-1}.

The carbon content in the husk of the Rudolfov hybrid is significantly higher than that of the Kulak hybrid, but no statistically significant difference was found between the other hybrids studied (Figure 4e). The dry matter yield of grain ranges from 9.92 to 11.28 t ha^{-1} and percentage of carbon between 40.01 to 41.72 % depending on maize hybride. The carbon content in the grain (Figure 4f) varies between 4.10 and 4.71 t ha^{-1}, and no statistically significant difference in the carbon content of the grain was found between the studied hybrids.



a) C content in root b) C content in stubble c) C content in stalk

d) C content in cob e) C content in husk f) C content in grain

Fig. 4 - Carbon content in: a) root, b) stubble, c) stalk, d) cob, e) husk and f) grain for each maize hybrid studied

By the literature review it was found that the Amos and Walters (2006) determined 0.64 t ha^{-1} of carbon in maize roots, which is almost half of the values determined in this study, and 0.29 t ha^{-1} in stubble, which is slightly lower than the value determined in this study. In the study conducted by Zhao et al. (2018), rhizodeposition was added to the belowground plant biomass, and the total value obtained was 3.00 t C ha^{-1}. Jans et al. (2010) found 0.40 t ha^{-1} of carbon in belowground biomass and 7.50 t ha^{-1} in the total aboveground biomass, which is lower than the values obtained in this study. Wang et al. (2022) determined the mass of carbon in the dry matter of the husk to be in the range of 0.48 to 0.65 t ha-1 , which is consistent with the valeus obtained in this study. According to Zhao et al. (2018), the husk contains 10 % of the carbon content in the stalk, which roughly corresponds to the values determined. Since the results from the literature review differ somewhat from the values obtained in this study, it can be attributed to the different morphology of the studied hybrids as well as the cultivation conditions.

Considering percentage of carbon content in the individual plant parts, Grignani et al. (2007) determied percentage of carbon content in root, stalk and husk of 40.0%, 45.0% and 47.0%, respectively. The obtained percentages correlate with the average values of the carbon content in the dry matter of same plant parts determined in this study, whose values on average amounts 36.6%, 46.6% and 46.4%, respectively.

CONCLUSION

The following conclusions can be drawn from this investigation:

1) no statistically significant difference between different hybrides in carbon content of:
   - cob (overall average value is 0.92 t C ha^{-1}),

- grain (total average value is 4.33 t C ha^{-1})

2) statistically significant difference between different hybrides in carbon content of:
   - root (Rudolfov and Kulak differ from OS 596 and OS 515; overall average value is 1.21 t C ha-1),
   - stubble (Rudolfov differ from OS 596, Rudolfov and OS 596 do not differ from Kulak and OS 515; overall average value is 0.40 t C ha-1),
   - stalk (Rudolfov differ from other hybrides; overall average value is 5.42 t C ha-1),
   - husk (Rudolfov differ from Kulaka, Rudolfov and Kulak do not differ from OS 596 and OS, 515; overall average value is 0.47 t C ha-1)

The study implicates that with selection of maize hybrides that sequestrate more carbon, as well with good biomass management more atmospheric carbon can be removed from the atmosphere and soil fertility can be increased

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ROBOTIC SYSTEMS FOR HARVESTING THE INFLORESCENCES OF MEDICINAL PLANT SPECIES - A REVIEW

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SISTEME ROBOTIZATE DESTINATE RECOLTĂRII INFLORESCENȚELOR UNOR SPECII DE PLANTE MEDICINALE - A REVIEW

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Keywords: *medicinal plants; harvesting; inflorescences; robotic systems.*

ABSTRACT

The use of medicinal plants and their derived products in the therapy of many diseases is common, with phytotherapy experiencing a strong revival in recent years. For certain species, only the inflorescences are harvested, due to their high content of bioactive compounds beneficial to human health. Although used since ancient times for their therapeutic properties as well as their sensory and nutritional characteristics, consumers continue to show interest in them. Moreover, the inflorescences of medicinal plants are sought after for the development and improvement of modern cosmetic products. Their manual harvesting requires a high labor input, which is difficult to achieve and sustain financially today. Due to specific technological requirements, the mechanized harvesting of inflorescences remains a challenge for researchers in the field, with numerous studies being conducted for its development and optimization. Technical progress requires the use of automated methods in the harvesting process. This paper provides a brief review of current research regarding the introduction of robotic systems for harvesting the inflorescences of certain medicinal plant species.

REZUMAT

Utilizarea plantelor medicinale și a produselor derivate în terapia multor boli, este frecventă, fitoterapia cunoscând un puternic reviriment in ultimii ani. De la anumite specii, se recoltează doar inflorescențele, datorită conținutului ridicat de compuși bioactivi, benefici pentru sănătatea umană. Deși utilizate din cele mai vechi timpuri, datorită proprietăților terapeutice, dar și a caracteristicilor senzoriale și nutriționale, consumatorii manifestă interes pentru ele. De asemenea, inflorescențele plantelor medicinale sunt căutate pentru dezvoltarea și îmbunătățirea produselor cosmetice moderne. Recoltarea lor manuală necesită un consum mare de forță de muncă, dificil de realizat și de susținut financiar astăzi. Datorită tehnologiilor specifice, recoltarea mecanizată a inflorescențelor rămâne o provocare pentru cercetătorii din domeniu, efectuându-se numeroase studii pentru dezvoltarea și optimizarea ei. Progresul tehnic impune utilizarea metodelor automatizate în procesul de recoltare. In aceasta lucrare se prezintă o scurtă sinteză a cercetărilor actuale privind introducerea sistemelor robotizate pentru recoltarea inflorescențelor anumitor specii de plante medicinale.

INTRODUCTION

For thousands of years, medicinal plants have represented a valuable resource for healing as well as for preserving the cultural characteristics of different ethnic groups *(Niazi et al., 2024; Fitzgerald et al., 2020)*. The phytotherapeutic action of medicinal plants refers to their beneficial effects on the health of the human or even animal body. Thus, flowers, leaves, stems, roots, fruits, or seeds of these species are used directly or in the form of preparations to prevent, treat, or cure various disorders *(Maldonata 2021*; *Jamshidi-Kia et al., 2018)*. Most useful parts of medicinal plants represent a rich source of biologically active substances, namely chemical compounds referred to as active principles.

The presence of some of these compounds influences the specific effects of these plants on the physiology of living organisms, particularly on human metabolism, which are enhanced through their synergistic action, leading to direct or indirect therapeutic effects *(Donkor et al., 2023; Jamshidi-Kia et al., 2018; Grigore et al. 2016)*. The value of medicinal plants is given by the natural bioactive compounds used in both traditional and modern medical practices *(Hosseinzadeh et al. 2015)*. Medicinal plants are harvested

during the period when the accumulation of active principles in their useful parts is at its maximum. The timing and method of performing this operation are essential for the quality of the plant material and, implicitly, for the pharmacodynamic action of these species *(Hazrati, S., Mousavi, Z., Nicola, S. 2024, Rao, K.S.; Haran, R.H.; Rajpoot, V.S. 2022)*.

The harvesting of inflorescences is a specific operation in the cultivation technologies of certain medicinal plant species, and its mechanized harvesting remains a constant challenge for specialists. This operation is common for chamomile (*Matricaria recutita* L.), marigold (*Calendula officinalis* L.), French marigold (*Tagetes patula* L.), and chrysanthemum (*Chrysanthemum indicum* L.), all belonging to the Asteraceae family. Inflorescence harvesting systems have been studied mainly for chamomile, later being applied to the other species mentioned above. Thus, they have been classified into comb-type systems with linear or rotary motion, with or without additional cutting, as well as rotor-type harvesters, characterized as a "virtual comb," equipped with pin drums and brush pairs *(Veselinov et al, 2014; Brabandt et al., 2011*; *Martinov et al., 2007)*. Numerous studies on mechanized harvesting systems for medicinal plant inflorescences have reported results regarding the working performance of various harvesting devices, including those designed for small areas, characteristics of the quality of harvested plant material, economic efficiency, etc. *(Mohamed et al., 2020; Radwan et al., 2015; Ivanović et al., 2014; Detlef et al., 2014)*. Medicinal and aromatic plants are part of the category of non-traditional food crops, being characterized by a higher market value compared to staple crops *(Taddei Dalla Torre et al. 2024)*.

In general, the harvesting of medicinal plant inflorescences represents an economic challenge for farmers, who must either have access to mechanized technical systems dedicated to this operation or to qualified labor. In the last 10 years, numerous studies have been carried out for the implementation of robotic technology for this purpose. Deep learning (DL) has been used as a tool to improve performance in computer vision and object detection. In addition, some mechanical systems have been optimized, being electrically operated and equipped with intelligent lifting (e.g., LiDAR-type) and control systems *(Liu et al., 2024; Zhou et al., 2019; Kamilaris et al., 2018)*.

This paper presents a brief synthesis of research results regarding the implementation of innovative intelligent systems in the automated harvesting process of chamomile (*Matricaria chamomilla*) inflorescences and certain edible plant species. For the latter, the focus has been on developing an artificial intelligence (AI)-based vision framework to support robotic harvesting, adaptable across different species and varieties.

MATERIALS AND METHODS

The development of a robotic system for chamomile inflorescence harvesting requires going through certain step-by-step stages (Fig. 1). These include: *Programming* - creating the detection model for the inflorescences; *Design stage* - integrating the mechanical elements of the system; and *Evaluation* - real-time assessment of the system *(Nasr et al., 2024)*.

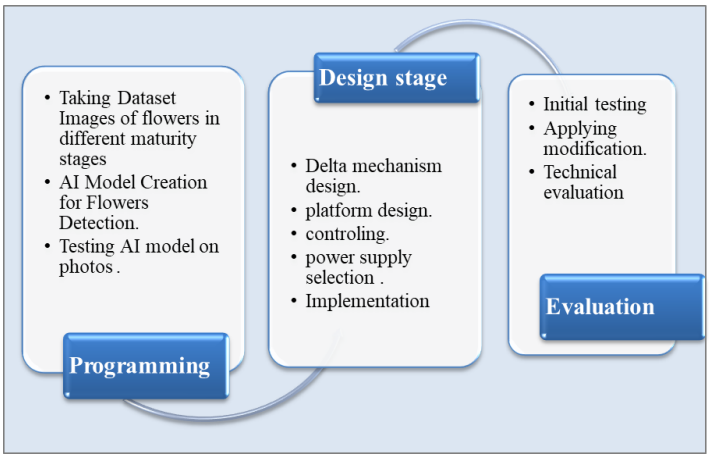


Fig. 1 - Stages in the development of a robotic system for chamomile inflorescence harvesting
(Nasr et al., 2024)

Within the *Programming* stage, in order to enable subsequent cutting, the classification of mature chamomile inflorescences was carried out using extended robotic tools. The detection model was created from a dataset of images of chamomile flowers at different phenological development stages, taken under

natural conditions. This model is compared with the data stream. A camera captures images of the flowers, and then, using an object detection algorithm to locate them instantly, the classification and filtering of mature chamomile flowers are performed.

The algorithm returns their coordinates, which are transmitted to an integrated system equipped with a microcontroller that controls the cutting and collecting mechanisms. For flower detection, using the TensorFlow machine learning system, the YOLO (v4) algorithm was combined with a deep convolutional neural network (CNN), developing a common interface *(Nasr et al., 2024)*. TensorFlow enables the implementation of machine learning models to be faster, more flexible, and more accessible for developers, assisting in data acquisition, prediction delivery, and refinement of future results. It is designed to run efficiently on various hardware components, being optimized for GPU (Graphics Processing Unit), but it can also operate with CPU (Central Processing Unit) *(Nur, 2022)*.

In the *Design* stage, the prototype of the Chamomile Flower Harvesting Robot – CFHR (Fig. 2) was developed, consisting of mechanical parts represented by the chassis, the delta robot mechanism, and the cutting mechanism, along with the control system *(Nasr et al., 2024)*.

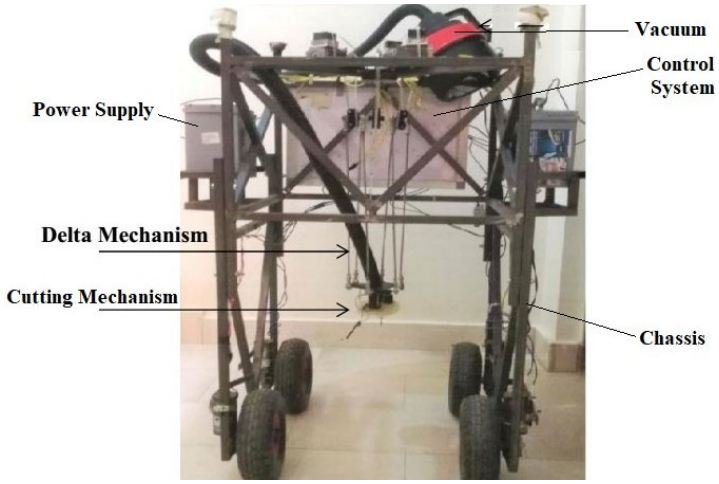


Fig. 2 - Chamomile Flower Harvesting Robot – CFHR

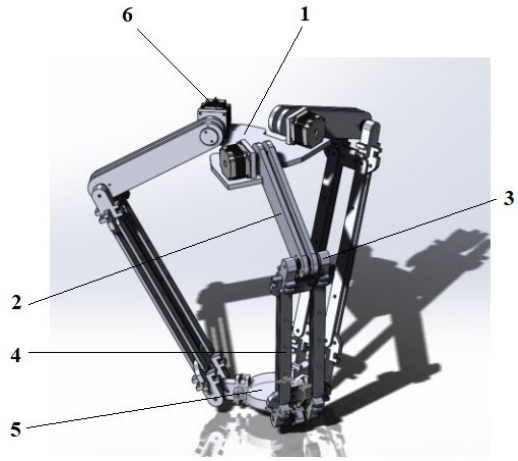


Fig. 3 - The delta robot mechanism

(adapted after *Nasr et al., 2024)*

The chassis (Fig. 2) is made of steel profiles (20×20×2), having a square shape of 0.6×0.6 m (L×W), with adjustable height up to 1.2 m. It is equipped with four durable rubber wheels, each with a diameter of 250 mm, driven by a 24 V DC motor. The delta robot mechanism (Figs. 2, 3) has the role of raising and lowering the cutting mechanism, being composed of: (1) Fixed base; (2) Input link; (3) Revolute joint; (4) Forearm; (5) Travelling plate; (6) Actuator. For this mechanism, the workspace was determined using numerical methods *(Nasr et al., 2024)*.

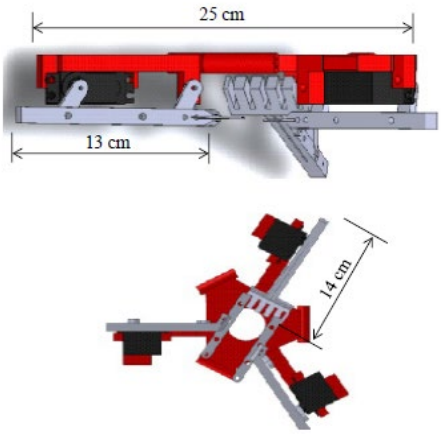


Fig. 4 - The cutting mechanism
(Nasr et al., 2024)

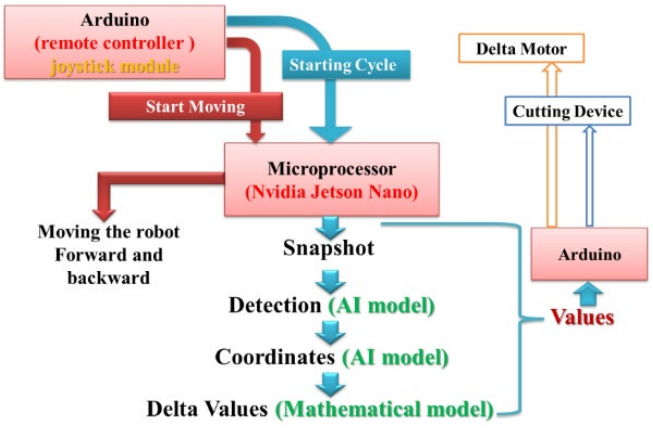


Fig. 5 - Control system diagram
(Nasr et al., 2024)

The cutting mechanism (Fig. 4) consists of a linear comb for flower fixation, complemented by a pair of cutting blades. Their role is to cut the flower stem after an appropriate time interval to ensure optimal harvesting results. Flowers with a petiole length of up to 50 mm are accepted, as first-quality flowers have petioles shorter than 10 mm, second-quality flowers have petioles of 10-30 mm, and third-quality flowers have petioles of 30-50 mm. The mechanism is actuated by three servomotors.

The control system (Fig. 5) consists of automation, monitoring, and control components. Its role is to visually detect chamomile flowers suitable for harvesting and to automatically command the mechanical elements to perform this operation. Thus, it includes: Raspberry Pi Camera Module, Nvidia Jetson Nano controller, Arduino UNO, stepper motors, DC motors, motor drivers, power supply, and battery.

To test and evaluate the robot's performance criteria, an experiment was conducted using 20 pots, each containing one chamomile plant (5 rows × 4 pots), simulating a spacing of 30 × 30 cm between plants in the field. The soil in the pots had a medium texture, with irrigation and fertilization carried out according to the recommended doses for chamomile cultivation. Under Egyptian conditions, the height of the cultivated chamomile plants ranged between 70 and 80 cm, with the average height considered to be 77 cm. At the peak flowering stage, each plant had between 15 and 25 flowers, distributed as shown in Figure 6 *(Nasr et al., 2024)*.

Fig. 6 - Flower distribution as percentage along plant stem
(Nasr et al., 2024).

With regard to the automated harvesting of certain edible plants, the study was carried out in a commercial greenhouse, focusing on several species important for the company's production. These were: French marigolds (*Tagetes patula* cv. Texana), snapdragon (*Antirrhinum majus*, cv. Leo), pansy and horned pansy (*Viola* × *wittrockiana* cv. Carneval and *Viola cornuta* cv. Sorbet, respectively), selected due to the distinct characteristics of their flowers as well as the morphology of the plants (Fig. 7). They were cultivated on benches with a height of 70 cm, a width of 110 cm, and a length of approximately 50 m. This method is commonly used in floriculture, providing favorable conditions for robotic harvesting *(Taddei Dalla Torre et al., 2024)*.
(*cv – cultivar)

a) French marigold (Texana) b) Snapdragon (Leo) c) Pansy (Carneval) d) Horned Pansy

Fig. 7 - Flower species considered in the experiments
(*Taddei Dalla Torre et al. 2024*)

For the estimation of the position and picking point, the flowers of the plants were examined: snapdragon flowers had an average diameter of 28 mm, marigolds 36 mm, while pansies reached up to 60 mm (both varieties being considered together).

Taking into account the cultivation method described above, a transport cart made of aluminum profiles with four wheels was built (Fig. 8). Its dimensions (width 120 cm, height 175 cm, track width 80 cm)

allow it to “straddle” the cultivation benches and move easily, with data (image) acquisition performed from the vertical position (Fig. 9) relative to the plants *(Taddei Dalla Torre et al., 2024)*.

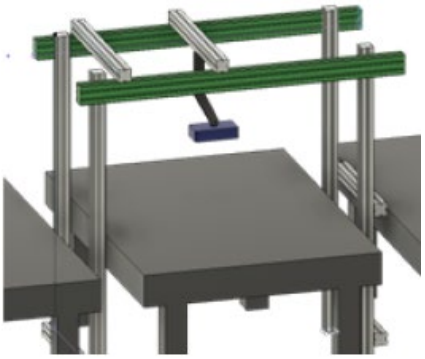


Fig. 8 - Straddle cart
(Taddei Dalla Torre et al. 2024)

Fig. 9 - Dates acquisition in greenhouse
(Taddei Dalla Torre et al. 2024)

Stereo RGB-D cameras were used: Zed 2 (field of view up to 120°, two 4 MP sensors of 2.1 mm in a native 16:9 format) and Zed 2i (field of view 81°, two 4 mm sensors with additional polarized filters). These generate a depth point cloud, associating a depth measurement with each captured pixel. The point cloud is derived using Neural Stereo Depth Sensing technology, with the cart being equipped with a Jetson TX2 module (a complete system-on-module developed by Nvidia, running AI models at the “edge,” i.e., configuring operations in real time). Using the combination of a Python GUI and Stereolab’s Python programming interface, Jetson TX2 can compute images and point clouds of the crop. Two data collection campaigns were conducted (on July 22 and November 17, 2023) for French marigold and snapdragon. For pansies, data were collected only in the last campaign. For model development and validation, the FloraDet dataset included 134 images containing a total of 2,443 flowers (Tab. 1). The Roboflow online annotation tool was used for manual labeling. According to the commercial quality standard, an edible flower is considered ripe and ready for picking when it has reached 70-80% of its full opening. Therefore, only flowers meeting this criterion were annotated *(Taddei Dalla Torre et al., 2024)*.

Table 1

Structure of the FloraDet dataset
(Taddei Dalla Torre et al., 2024)

	Items	French marigold	Snapdragon	Pansy
July	Images	25	13	-
	Flowers	854	762	-
November	Images	21	11	64
	Flowers	401	51	375

By merging images from two distinct sources (ImageNet and Kaggle), an additional dataset D0 was created for preliminary testing and fine-tuning of the AI model. Thus, dataset D0 included flower species different from those in FloraDet and was further enriched with images of pansy flowers, due to their variability as well as their underrepresentation in the initial dataset.

Figure 10 shows the operational workflow composed of three individual modules: *Flower Detection*, *Pose Estimation*, and *Plucking Point Estimation (Taddei Dalla Torre et al., 2024)*.

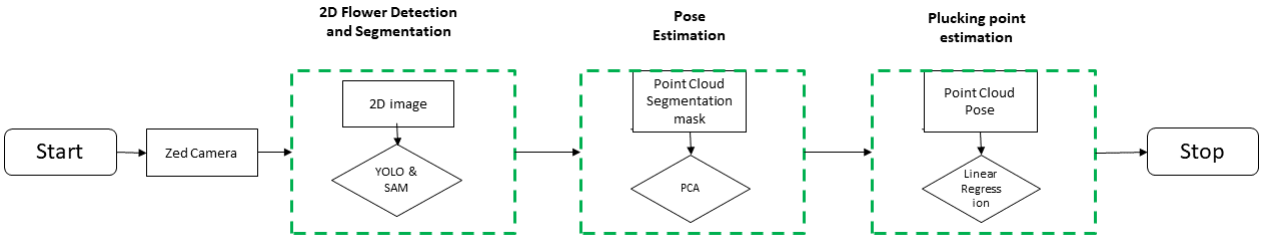


Fig. 10 - Operational workflow
(*Taddei Dalla Torre et al. 2024*)

In the first module, *Flower Detection*, an image together with the bounding boxes predicted by YOLO is fed into SAM (Software Asset Management), generating a binary mask as output, which effectively separates the pixels corresponding to flowers from other objects *(Taddei Dalla Torre et al., 2024)*.

In the next module, *Pose Estimation*, the flowers in the input image are segmented by SAM, with the generated binary mask used for each flower of interest to extract a point cloud. Once the point cloud is extracted, the PCA algorithm is applied to identify the vector components describing its distribution. The pose of the flower is then determined from the PCA (Principal Component Analysis) axes (Fig. 11) *(Taddei Dalla Torre et al., 2024)*.

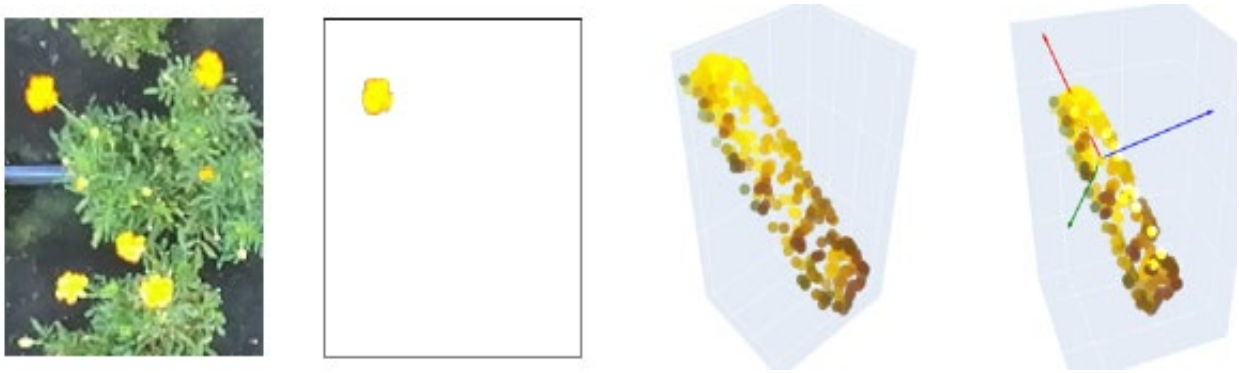


Fig. 11 - Flower pose estimation

From left to right: input image, single flower cutout trough SAM, derived isolated point cloud in the 3D space, and PCA-based point cloud analysis

(*Taddei Dalla Torre et al. 2024*)

At the end of the operational workflow, the visual framework includes a module designed to estimate the optimal picking point of the flower. An attempt was made to identify this picking point, located just below the calyx, but this was not achieved due to occlusion caused by the flower itself or by surrounding leaves. In the case of flowers, 3D matching cannot be applied due to their complex and variable morphology, the method being applicable only to denser objects with well-defined shapes.

Figure 12a shows the previously calculated flower position vectors together with the extension of the vertical component aligned with the optimal picking point. To estimate this, an attempt was made to define a numerical relationship between d - the flower diameter (Fig. 12b) and h - the distance from the flower apex to the picking point (Fig. 12c).

For this purpose, 300 flowers from the three species of interest were measured, from the same rows where the images were captured *(Taddei Dalla Torre et al., 2024)*.

a) Marigold flower featuring pose vectors and the plucking point (side view)

b) Marigold flower, showcasing its circumference and diameter **d** (top view)

c) Marigold flower, highlighting height and plucking point **h** (side view)

Fig. 12 - The side and top view of a marigold flower

(Taddei Dalla Torre et al. 2024).

RESULTS

The technological performance of the chamomile harvesting robot was analyzed by evaluating several parameters throughout a harvesting cycle carried out in three stages. Table 1 provides a synthesis of the results obtained.

Table 2

Synthesis of results

(adapted from *Nasr. et al., 2024).*

Parameter		Collection times			
		1st	2nd	3rd	Average
Harvesting time for one plant [s]		13	22	28	21
Total harvesting time for a row of pots [s]		52.15	88.20	112.20	84.18
Flower number for one plant		4	7	9	6
Total harvesting time for experimental pots [min]		10.35	13.95	17.35	13.88
Harvesting success ratio for CFHR during harvesting season [%]		75.0	85.70	89.7	83,47
Visual selection evaluating parameters for CFHR	Accuracy [%]	72,4	59,5	53,9	61,93
	Detection precision rate [%]	75,0	50,0	49,7	58,23

Figure 13 shows the quality of chamomile flowers harvested by CFHR during the three collection periods. The results obtained were compared with those from manual harvesting under the same conditions.

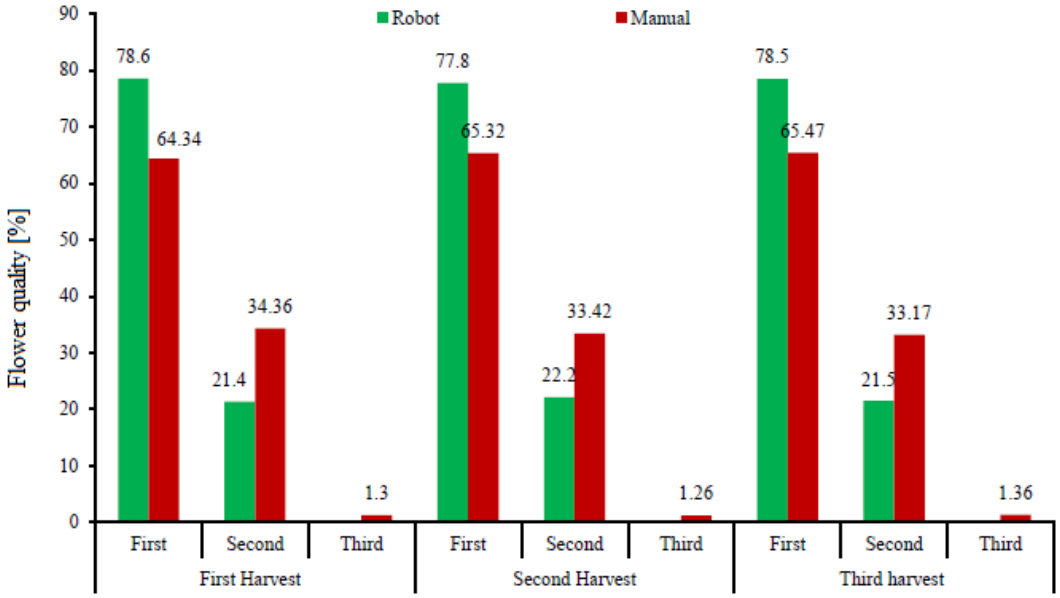


Fig. 13 - Quality of chamomile flowers harvested with CFHR and manually

(Nasr et al., 2024).

With regard to the automated harvesting of edible plants, the relevant results corresponding to each module of the operational workflow are presented. Detection was the only aspect subjected to training and evaluation. The models were obtained after two fine-tuning processes, with the respective datasets split into 75% for training, 15% for testing, and the remaining 10% for validation.

The optimal models were selected based on the period during which, on the validation set, the model achieved the highest performance.

The low value of 0.045 for the object detection error on the validation set demonstrated the effectiveness of the model in accurately identifying and locating flowers at the harvesting stage (Fig. 14) for marigold and snapdragon.

In the case of pansies, the model results were not relevant due to the limited amount of data as well as the natural variability within the species, which in this case included two distinct cultivars *(Taddei Dalla Torre et al., 2024)*.

Fig. 14 - Cropped images from FLOLO model detection results (Mar=Marigold; Snap=Snapdragon representing flowers ready for harvesting)
(*Taddei Dalla Torre et al. 2024*).

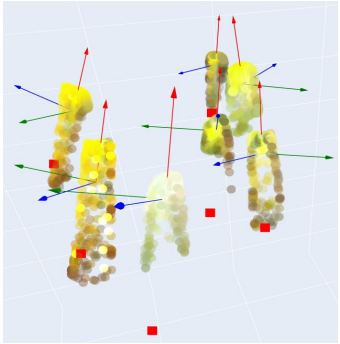
With regard to determining the position of the flowers to be harvested, after applying the PCA algorithm, the vector component was calculated for each corresponding point cloud, following their isolation by the binary segmentation mask. In some cases, the segmentation masks may include separate polygons for the same bounding box of the prompts, since each bounding box contains a single flower. Therefore, it was necessary to eliminate some of these polygons. For this purpose, the center of each polygon was extracted, and only the mask with the centroid closest to the center of the bounding box was selected. This mask was then used to filter the pixels in the 3D point cloud that were not identified as detected flowers *(Taddei Dalla Torre et al., 2024)*. With regard to the estimation of the harvesting point position, for each species it was considered that a potential relationship between **d** and **h** could be evaluated through linear regression. Eighty percent of the measurements were used to investigate the relationship, while the remaining 20% were used for testing. Table 3 presents the corresponding equations for the linear regression and the respective upper boundary for each flower type. To mitigate possible flower damage, the estimation module used a translated line corresponding to the upper limit of the 85% confidence interval to determine **h** as a function of **d** *(Taddei Dalla Torre et al., 2024)*.

Table 3

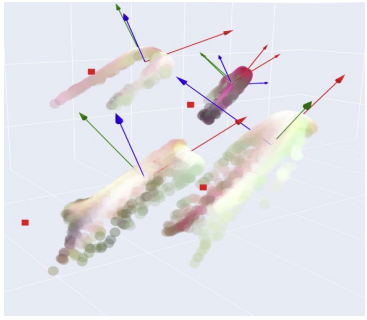
Equations for the linear regression and the respective upper boundary for each of the different flower types
(*Taddei Dalla Torre et al. 2024*)

	Pansy	Snapdragon	Marigold
Linear Regression	$h_v = 0.36d_v + 26.33$	$h_s = 0.38d_s + 5.33$	$h_m = 0.66d_m + 7.10$
Upper boundary	$h_v = 0.36d_v + 43.20$	$h_s = 0.38d_s + 34.57$	$h_m = 0.66d_m + 37.91$

The flower diameter **d** was calculated by estimating the smallest convex polygon enclosing the points, taking into account the binary mask. The flower's central point is located among the upper points of the 3D cloud and is defined as the point within the polygon situated at the maximum distance from the polygon boundary. The distance **h** was calculated using the equations presented above. Once the flower position was determined, the central point was translated downward along the main vertical vector by the calculated distance **h**. This point represents the estimated optimal picking point and is marked with a red square in Figure 15 *(Taddei Dalla Torre et al., 2024)*.



Marigold



Snapdragon

Fig. 15 - Isolated point clouds of marigold and snapdragon flowers and the respective vector components (red, green and blue vectors) and estimated picking point (red squares)
(*Taddei Dalla Torre et al. 2024*).

Table 5 presents the average time (s) required for processing the validation images with a variable number of flowers for two species of interest. The averages are calculated based on the analysis of 10 images for each species, including a total of 457 marigold flowers and 975 snapdragon flowers *(Taddei Dalla Torre et al., 2024)*.

Table 4

Average processing inference time (s) for each step of the AI framework on an NVIDIA GeForce RTX 3090

(*Taddei Dalla Torre et al. 2024*)

	Detection	Localization			Estimation		Total Time	Time per Flower
	YOLO	SAM	Clean Masks	Isolate 3D Poins	Pose (PCA)	Picking Points		
Marigold	0.285	4.37	0.08	42.36	1.44	1.48	48.35	1.064
Snap dragon	0.293	4.36	0.165	89.90	5.76	5.87	95.99	0.98

The processing times obtained in this study (1.064 s for marigold and 0.98 s for snapdragon) are comparable to the values reported in the literature by *Li et al. (2023)*. These results demonstrate that the tested procedure can be implemented in the field, with the total time required for processing a single flower representing the key indicator for this perspective.

CONCLUSIONS

For the performance indicators, the results obtained for the chamomile harvesting robot demonstrate the viability of the proposed solution. Considering that these were obtained at the experimental stage, further research and development are necessary. In the chamomile harvesting process, future work should focus on increasing the success rate, productivity, accuracy, and efficient use of working time.

With regard to the robotic harvesting of edible flowers, the study evaluated the viability of an artificial intelligence (AI)-based vision framework, as well as its performance across different species. By adjusting the workflow, the general framework could also be applied to the validation stages of field inferences. Ensuring the effectiveness and reliability of the framework in real agricultural environments will require rigorous testing and validation through extensive further research. The detection, position estimation, and picking point estimation capabilities of the framework represent a premise for robotic harvesting, with implications for increasing efficiency for growers.

The robotic harvesting of medicinal and edible plant inflorescences could represent a socio-economically sustainable alternative to manual harvesting.

ACKNOWLEDGEMENT

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THE EU DIGITAL PRODUCT PASSPORT DPP AS A KEY INNOVATION IN PRODUCT DESIGN AND MANUFACTURING PROCESSES

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PAŞAPORTUL UE DE PRODUS DIGITAL DPP CA O INOVAȚIE CHEIE ÎN PROIECTAREA PRODUSELOR ȘI PROCESELE DE FABRICAȚIE

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Keywords: *digital product passport, data requirements,* product transparency and sustainability

ABSTRACT

Sustainability and circularity are quickly becoming a key strategic priority for organizations, brands and even consumers. Digital Product Passports (DPPs) are designed to collect and share data about a product and its supply chain across the entire value chain. As Digital Product Passports impact and involve multiple stakeholders from across value-chains and sectors – the benefits and value are far reaching. From organizations, to consumers, to policy makers and recyclers – digital passports provide benefits for all. This paper presents what is known about digital product passports, such as who needs to comply, what data needs to be included in a DPP, how to implement a DPP system, and its importance and benefits.

REZUMAT

Sustenabilitatea și circularitatea devin rapid o prioritate strategică cheie pentru organizații, mărci și chiar consumatori. Pașapoartele pentru produse digitale (DPP) sunt concepute pentru a colecta și a partaja date despre un produs și lanțul său de aprovizionare de-a lungul întregului lanț valoric. Pe măsură ce pașapoartele pentru produse digitale au impact și implică mai multe părți interesate din toate lanțurile valorice și sectoare, beneficiile și valoarea sunt de mare anvergură. De la organizații, la consumatori, la factorii de decizie și reciclatori – pașapoartele digitale oferă beneficii pentru toți. Această lucrare prezintă ceea ce se știe despre pașapoartele pentru produse digitale, cum ar fi cine trebuie să se conformeze, ce date trebuie incluse într-un DPP, cum se implementează un sistem DPP și importanța și beneficiile acestuia.

INTRODUCTION

The reason that digital technologies should be able to facilitate circularity in the economy is that circular as opposed to linear production, consumption and disposal will require far more communication and exchange of data and information between the various links in the life cycle of products. Here's why the European Union *(European Commisson, 2022; EURACTIV, 2021)* has the initiative of establishing a Digital Product Passport (DPP).

A Digital Product Passport (DPP) is a digital record that provides comprehensive information about a product and its entire value chain, including everything from the origin of the product, materials used, environmental impact, and disposal recommendations *(King et al, 2023).*

DPPs' main purpose is to close the gap between the transparency demanded by consumers, investors, and other stakeholders and the current lack of reliable data on product journeys *(Baumgartner, 2023).*

The Digital Product Passport DPP will include essential details such as a unique product identifier, compliance documentation and information on substances of concern. It will also provide user manuals, safety instructions, and guidance on product disposal. By offering a detailed digital record of a product's lifecycle, the DPP will enhance supply chain management, ensure regulatory compliance, and help companies identify and mitigate risks related to authenticity and environmental impact *(Berger et al, 2023).*

DPPs enable all stakeholders, including consumers, to gain a deeper understanding of the materials used in products and their associated environmental impacts […].

On the other hand, Digital Product Passports DPP are a mandatory component of the Ecodesign for Sustainable Products Regulation *(ESPR, 2022)* and one of the key actions under the Circular Economy Action Plan *(CEAP, 2022).* Under the ESPR, all regulated products — including textiles, construction materials, industrial and electric vehicle batteries, and at least one additional key value chain identified in the Circular Economy Action Plan, such as consumer electronics, packaging, or food — will be required to implement DPPs.

This means that once Ecodesign for Sustainable Products Regulation *(ESPR, 2022)* is formally adopted, sustainable products will be the new benchmark for smart business.

DPP are also not a stand-alone idea; they are part of a broader framework that includes elements of traceability, chain of custody, supply chain collaboration, and data-sharing requirements, all of which are integral to a range of other regulations. These all, form part of the European Union's Digital Transition and Data Spaces plans designed to harmonize and standardize access to data *(European Commission, 2020).*

Blockchain technology provides a clear and verifiable record of product and travel information, making it easier for consumers to make informed choices based on the origin, sustainability, and authenticity of a product, improving transparency *(Damvakeraki, 2024).*

As Digital Product Passports impact and involve multiple stakeholders from across value-chains and sectors – the benefits and value are far reaching. Digital passports provide benefits for all interested parties, from organizations, to consumers, to policy makers and recyclers.

By pursuing early compliance and adopting voluntary certifications, companies can capture a larger market share. As traceability becomes a basic requirement for material procurement, developing robust product traceability and supply chain impact-tracking methods will position businesses as leaders *(Neligan et al., 2023; Sudusinghe and Seuring, 2022).*

This paper presents what is known about digital product passports, such as who needs to comply, what data needs to be included in a DPP, how to implement a DPP system, and its importance and benefits.

MATERIALS AND METHODS

Digital Product Passport DPP's implementation

The Digital Product Passport DPP's implementation aligns closely with open data principles by making detailed product information publicly available *(Henten et al, 2025).* This approach will not only improve product visibility and sustainability practices but also facilitate better data sharing and collaboration across the industry. Open data's role in this context highlights the importance of accessible, standardised information in driving transparency and accountability *(Gieß and Möller, 2025; Jensen et al, 2023).*

A DPP is a tool aimed at enhancing transparency about a product's environmental impact by offering relevant and comprehensive information about its lifecycle (see figure 1).

Similar to traditional passports, each product has a unique identity that's linked to one source with information about just that specific product.

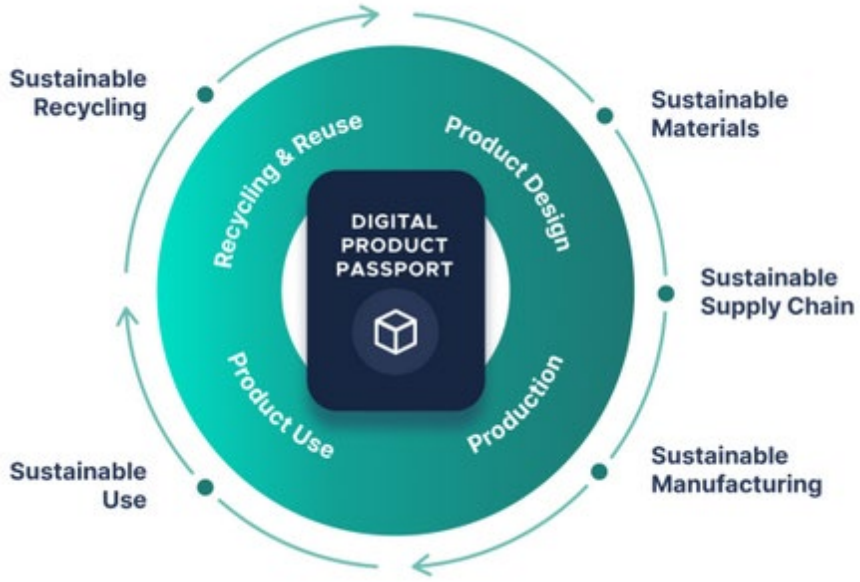

Fig. 1 - Dimensions of Digital Product Passport (DPP)

A DPP will soon be required for a range of products. Products with a high environmental impact and potential for improvement (textiles, furniture, chemicals, batteries, consumer electronics, electronic devices and construction products) will be prioritized.

The implementation of digital product passports in these value chains is designed to support:

- **Sustainable product production**: boosting material and energy efficiency, extending product lifetimes, and optimizing product use.
- **Businesses to create more value through circular business models**: improved access to data with digital product passports, more businesses can implement service and repair-based business models.
- **Consumers to make more informed purchasing decisions:** providing them with accurate information on the true impact of their buying behaviours.
- **Compliance with legal obligations:** product complies with standards and provide auditors with information to evaluate and verify.

According to the *(EU ESPR, 2022),* the first batch of products that need to have DPPs include: iron and steel, aluminum, textiles (garments and footwear particularly), furniture, tyres, detergents, paints, lubricants, chemicals, energy-related products with ecodesign requirements, information and communication technology products and other electronics *(Schuberth et al, 2024).*

Starting with 19 April 2025, manufacturers, importers, distributors, and retailers of these products must make their DPPs accessible. More categories will be known in the upcoming years, as the Commission is set to regularly update the list of products having to comply with the Regulation.

The textiles, construction, electronic waste, plastics, chemicals, and automotive sectors are all experiencing significant pressure and initiatives to adopt more sustainable business practices. Legislation is being developed to create connections across these various product categories, reflecting the growing emphasis on digitization, interconnected data sets, and the assessment of environmental impacts throughout product life cycles *(Panza et al, 2023; Saliger et al., 2024; Veenstra et al, 2025).*

Data requirements for digital product passports

Data requirements for DPP have been defined by the Ecodesign for Sustainable Products Regulation *(ESPR, 2022),* but implementation calls for the whole supply chain to cooperate and define the crucial information that could prevent a product from going to waste.

While DPP solutions can be adapted to a number of different use cases and can include various features and functionality, the ESPR outlines a number of key Digital Product Passport requirements for compliance that can be categorized into three key categories *(Framling et.al, 2007),* which include general requirements, access requirements and data requirements (see figure 2).

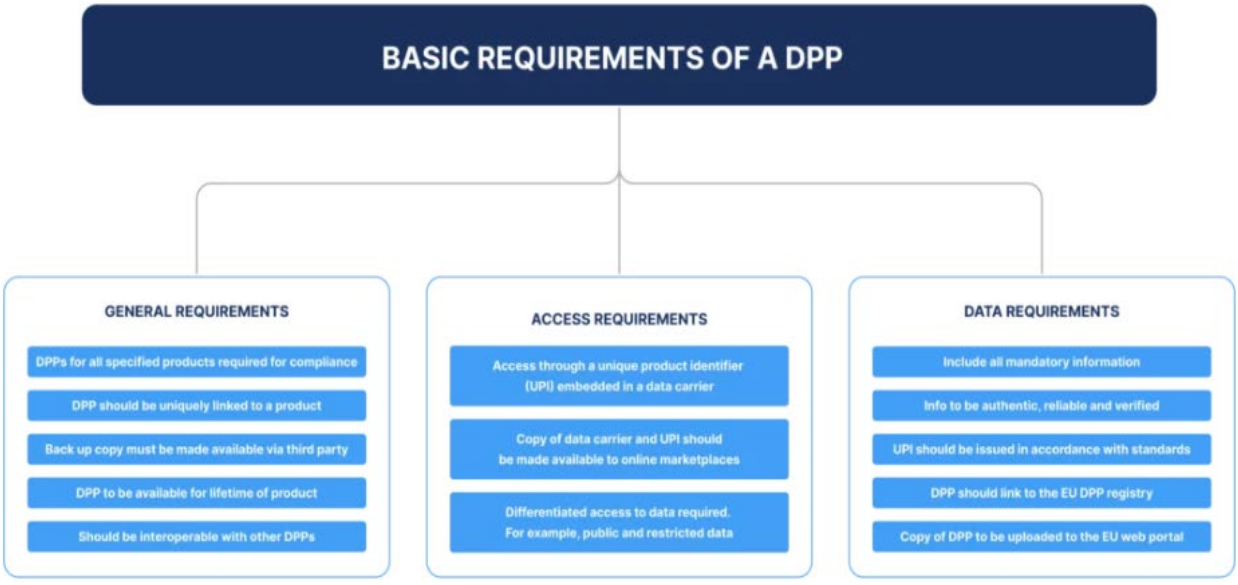

Fig. 2 - Overview of the basic requirements of a Digital Product Passport according to the ESPR.

General DPP requirements include:

- Passport should exist and be in compliance with essential requirements
- A DPP should be uniquely linked to a product.
- A back up copy must be made available via third party product passport service provider.
- The passport must remain available for at least expected lifetime of product.
- A DPP must be fully interoperable with other digital product passports.

The data requirements for DPP are:

- **Unique Product Identifier.** Each DPP links to a unique product ID via a data carrier (e.g., barcode, QR code) placed on the product, its packaging, or in accompanying documentation.
- **Compliance with Global Standards.** The DPP follows *(ISO, 2015)* standards to ensure consistency, quality, and global interoperability.
- **Structured, Machine-Readable Data.** All information in the DPP is structured, machine-readable, and based on open standards, making it searchable and compatible with digital systems.
- **Comprehensive Product Information.** The DPP contains key details about the product model, batch, or individual item, enhancing transparency across the supply chain.
- **Controlled Access to Information** Access to DPP information is regulated per Article 10, with specific access levels for each product group as set by Article 4 *(ESPR, 2022).*

Implementing a data transfer infrastructure for DPPs

Once a framework is defined for the information to be included in DPP, traceability software can be used to standardize data sets coming from existing ERP systems. The required unique product identifiers can use existing technologies such as barcodes, QR codes, Radio-frequency identification (RFID) tags, or similar, for digital product passport data submission. In the end, this process can be almost entirely automated.

In most cases, the main gap for companies lies in establishing the infrastructure for an open, standard, interoperable format for the DPP data – one that is also machine-readable, structured, and searchable, as outlined in the essential requirements of Article 9 of *(ESPR, 2022).*

The rapidly developing of blockchain and decentralized systems will be able to meet these requirements and provide key product information to the parties who value it most. These technological advances also mitigate the past criticism that decentralized blockchains have high operating costs and energy consumption. New blockchain technology developments will allow vast amounts of secure data transfer.

Protecting proprietary information by blockchain technology

When creating digital product passports, ensuring data security is essential for the protection of trade secrets. Different industries will require tailored approaches to data storage and encryption to address security challenges. Data storage can either be centralized or decentralized; but given the significance of the data being shared, a centralized system with a private party in control of data storage and integrity could be a less secure scalable solution for DPP infrastructure (. In some instances, a decentralized system provides the most effective means of data interoperability *(Damvakeraki and Vlachos, 20240).*

Decentralization also means the owner of the product is also the owner of the digital record, preventing reliance on a centralized system where data could be vulnerable to tampering. This approach complements the EU Data Strategy *(EURACTIV, 2021),* which encourages the use of high-value, publicly accessible data to generate value for companies, governments, and consumers. Circularize 's product traceability system is customizable, enabling businesses to opt for a public, decentralized blockchain for enhanced transparency and security if needed.

Blockchain technology acts as the perfect foundation on which to build a DPP solution for several reasons such as:

- **Data Security:** A consensus approach to validating data, underpinned by the most robust encryption system virtually eliminates data tampering and fraud. Decentralized technology also removes single points of failure securing data like never before.

- **Immutability:** As an immutable digital ledger, blockchains offer an extremely high level of trust in the data they contain. Consensus-based data validation guarantees that the information held is accurate and hasn't been changed or tampered with by malicious parties.
- **Transparency:** All blockchain transactions are provable, traceable and searchable on-chain, providing complete transparency for all ecosystem stakeholders in relation to the data stored within DPP.
- **Efficiency:** Data is processed, exchanged and validated quickly with blockchain.
- **Decentralization:** Blockchains are decentralized, censorship-resistant, and less vulnerable than legacy technologies that rely on centralized servers.

The key advantages of using blockchain for digital product passports, therefore, include improved transparency, less fraud, improved compliance, sustainability, supply chain efficiency, and consumer empowerment.

Marketing, sales and customer success teams can all utilize the digital passport application as a means of offering new services or features that are otherwise unavailable.

Essential Steps to Prepare for DPP Compliance

Efficient management of product data requires a Product Information Management (PIM) system, which serves as the backbone for ensuring consistent and transparent product information across all channels - a critical factor in meeting DPP requirements and building customer trust.

Fig. 3 - Key information in a Digital Product Passport

To prepare for Digital Product Passport (DPP) compliance, businesses need to first understand the regulations and their specific scope, then conduct a thorough product audit, and finally develop and implement a comprehensive data management strategy, including establishing traceability. This includes gathering product data, creating unique identifiers, and ensuring data security and interoperability (Navarro et al.,2022; Zhang and Seuring, 2024).

When taking a more holistic view of Digital Product Passports in terms of their current and potential utility – there are multiple different data categories that can be collected (see figure 4).

Fig. 4 - An example of the data sets that DPP can include

As previously mentioned, Digital Product Passports as a technology is still early and use-cases continue to grow – directly tied to the type of data being collected. Ultimately, DPP provide multiple parties including manufacturers, consumers, re-sellers and recycling entities with a full audit-trail of events and transactions that have occurred through a product's life.

For now, the key focus is on the sustainability, repairability and recyclability of a product that all ties into the broader circularity of the actual product. But as more businesses dive into the technology and understand its potential, DPP use-cases and opportunities will continue to scale.

Data Carrier

Data carriers refer to the mechanism that enables end-users to access the Digital Product Passport tied to a particular product. At present, EU guidelines suggest that organizations will have the freedom to decide what data carriers they utilize for any single, batch or type of product. Data carrier types suitable for DPPs include:

- **QR Code:** Already commonly utilized across several different industries and verticals for a multitude of purposes – the QR code could be considered the current go-to data carrier. Also famed for its durability and flexibility, QR codes are also widely accessible due to their easy connectivity with a smart device.
- **Barcode:** A similar option to the QR code carrier type, but offering less flexibility in terms of data held and utility due to its general purpose being to store product basic data and not for example, act as a conduit between a user and a webpage (that could contain the associated DPP).
- **NFC:** Already used for contactless payments, Near Field Communication (NFC) are similar to QR codes in that they are accessible by the majority of modern days smart devices, although they do carry additional cost as they are essentially standalone hardware devices (stickers with embedded antenna and microchip). A large advantage non-fungible token (NFT) tags have over QR & barcodes is their ability to be installed 'inside' a product and not necessarily on the 'outside' that offers further security benefits.

Data Sharing

Given the broad number of stakeholders and entities that participate in any given value chain, along with the varied demands and usage of data – a DPP solution will require a flexible approach to data sharing and accessibility.

Current proposals will categorize data stored within the DPP between private or public – whilst permissions to access, modify or update data will be defined by the European Commission. Although specific delegated acts to formalize DPPs for each target industry are still under development, the Commission has ensured that data security and privacy is at the heart of DPP design.

RESULTS

The benefits of implementing Digital Product Passports are:

- **Enhanced transparency**: DPPs provide companies with detailed information about their products' origin, materials, and environmental impact. This enhances global visibility for a company's brand and towards its customers.

- **Improved supply chain management**: The passports offer a comprehensive digital record that spans a product's entire value chain. This enhanced visibility enables companies to optimize processes to reduce environmental impact and ensure a more sustainable and efficient supply chain.

- **Regulatory compliance**: The DPP ensures that companies can easily adhere to environmental standards and regulations, fostering a commitment to responsible and sustainable business practices.

- **Identifies risks**: The DPP spots potential and actual risks by collecting clear information, real-time monitoring, and collaborative data sharing. It helps companies catch problems with authenticity, compliance, and environmental impact, taking a proactive approach to minimize risk.

- **Builds trust**: By providing transparent and verifiable information on a product's origin, authenticity, and compliance with relevant standards, the passports will help companies to build trust among customers, investors, and other important stakeholders.

The benefits to Businesses and Organizations are:

- **New Business Models:** The push towards a circular economy with more focus on product longevity provides a plethora of new business opportunities (such as product-as-a-service) that can be utilized to unlock additional revenue streams and growth drivers for companies. Digital passports can be seen as an additional channel that marketing, sales and business operations can tap to provide new services and an enriched customer experience.

- **Increase Consumer Trust:** By recording events across the full lifecycle of products from manufacturing all the way to recyclability or disposal – businesses can offer consumers a fully transparent view into the authenticity and state of the product they are purchasing.

- **Validate Green Claims**: Greenwashing is becoming a serious issue that is tainting the reputation of companies who are making legitimate claims. Through a digital passport, the sustainability attributes and claims are fully validated and secured on an immutable blockchain network.

- **Consumer Protection**: By ensuring that the raw materials and manufacturing processes abide by pre-set standards, businesses can protect their customers from illegitimate, dangerous and sub-par raw materials and end-products.

- **Ensure Compliance:** Through digital passports as a single and shared source of truth, the required data can be more easily tracked and accessed, leading to businesses being able to track their compliance with initiatives in real-time.

- **Quality Control:** The verifiable product data collected at each production stage by DPPs can allow businesses to improve their quality control measures.

- **Promote Sustainable Manufacturing:** From the provenance of sustainable raw materials used to providing operational data for improved oversight of the manufacturing process, DPPs

promote circularity and sustainability in manufacturing and can help minimize the negative impacts of production.

The benefits to Consumers and End-Users are:

- **Buyer Confidence:** Digital passports enable consumers to make more informed purchase choices related to the sustainability performance of the brands they buy from**.**

- **Maximized Product Value:** Similar to the above, consumers can rest assured that their products are legitimate – enabling them to avoid faulty or forged goods.

- **Identify Greenwashing:** Digital passports are a perfect tool to enable consumers to identify greenwashing and validate a company's claim in relation to their green initiatives. Though the immutability and transparency provided by blockchain, consumers can identify whether they are being purposely misled.

- **Recognize Carbon Footprint:** Many consumers who are seeking more sustainable responsibility from their chosen brands are looking to improve their own performance and reduce their carbon footprint. Depending on the type of product, accurate data on energy consumption and environmental impact can be gathered from an associated digital passport, which could also include additional blockchain-enabled services. Blockchain and digital passports opens new doors for encouraging positive action from consumers in joining the pledge to champion circularity.

- **Selecting Quality Products:** For customers, being able to compare the quality of two similar products side by side can make their purchase decision easier. Organizations can demonstrate that their products meet the highest quality standards by including certifications and warranties within their DPP, which the customer can easily access in a transparent and verifiable manner.

The benefits to Policy Makers and Governing Bodies are:

- **Verify Compliance:** DPP's provide a unified basis for tracking the sustainability performance of business entities and organizations, providing a mechanism for policy makers to benchmark KPI's and take necessary action if required.

- **Drive Sustainability:** Under a digital passport system, greenwashing and false claims are significantly reduced, giving policy makers the best chance of meeting their key sustainability, resource optimization and circularity goals.

CONCLUSIONS

- The Digital Product Passport represents a significant advance in product transparency and sustainability. As the EU moves towards full adoption of this regulation, it will foster a more open and responsible marketplace.

- By integrating open data principles, the DPP will enhance both the visibility and integrity of product information, benefiting companies, consumers, and the environment alike.

- Going through the process of DPP implementation will also enable manufacturers to gain a clearer view of their material flows and process efficiencies, paving the way for impactful improvements.

- By addressing and mapping out sustainability roads through the entire product lifecycle, emphasising the importance of transparency, supply chain traceability and accountability, the ESPR fosters a culture of sustainability and brings the EU one step closer to the goals of the European Green Deal.

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RESEARCH ON THE INFLUENCE OF RAW WOOL QUALITY ON THE PARAMETERS FOR OBTAINING HYDROLYSATE BY THE ALKALINE METHOD

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CERCETARI PRIVIND INFLUENTA CALITAȚII LÂNII BRUTE ASUPRA PARAMETRILOR DE OBȚINERE A HIDROLIZATULUI PRIN METODA ALCALINĂ

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ABSTRACT

Wool waste or unsaleable wool is a growing resource in Europe, which, due to the low biodegradability of keratin, can be a source of long-term environmental pollution. At the same time, the chemical composition of wool, especially keratin, is a protein compatible with cell growth and has a high sulphur content, which is important in the formation of proteins, enzymes, vitamins and chlorophyll in plants. A simple method for solubilising keratin from wool is alkaline hydrolysis. In this regard, our research has investigated the influence of wool waste quality on the parameters of the alkaline hydrolysis process (temperature, processing time) and on some physical properties of the hydrolysate obtained (degree of decomposition, undegraded residues).

REZUMAT

Deseurile de lana sau lana nevandabilă reprezinta o resursa in crestere la nivel european, care datorita gradului redus de biodegradare a keratinei poate constituii o sursa de poluare pe termen lung a mediului. Totodata compozitia chimica a lanaii, in special keratina reprezinta o proteina cu compatibilitate pentru cresterea celulara si cu un continut ridicat de sulf-element important in formarea proteinelor, enzimelor, vitaminelor si clorofilei in plante. O metoda simpla pentru solubilizarea keratinei din lana o reprezinta si hidroliza alcalina. In acest sens cercetarile au urmarit influenta calitatii deseurilor de lana asupra parametrilor procesului de hidroliza alcalina (temperatura, durata de procesare, si asupra unor proprietati fizice a hidrolizatului obtinut (grad de descompunere, resturi nedegradate).

INTRODUCTION

The global sheep population stands at approximately 1.27 billion head, with a production of approximately 1.9 million metric tons of wool (*IWTO, 2022*). At EU level, it is estimated that there are approximately 85 million sheep in various production systems (*Theodoridis et al. 2021*), with an annual wool production exceeding 200,000 tons, classified into several groups (*Petek and Marinšek Logar 2021*). In 2024, Romania was ranked in second place with a total of 11.87 million sheep (*https://www.stiripesurse.ro/romania-urca-in-topul-european-cu-peste-11-milioane-de-oi-si-capre-locul-2-in-ue-dupa-spania_3685104.html*).

Approximately 60% of wool is used in the production of woolen clothing (*Woods, 2012*), which has continued to experience a decline in demand, leading to the elimination of large volumes of low-quality wool (*Ossai et al., 2022*). Cheap, low-quality wool is mainly considered a by-product (*Chereji and Munteanu 2022*).

Due to the economic situation, raw wool production is an economic burden for sheep farmers in many EU countries, although wool is a biological resource rich in protein (95%–98% of wool weight) that is available in large quantities and at affordable prices.

Wool waste significantly affects the biological properties of soil (*Lal et al. 2020*). β-glucosidase activity, which plays a crucial role in the decomposition of cellulose and the cycling of carbon within the soil, has been shown to increase with sheep wool treatments (*Çetin Karaca et al. 2023*).

Wool is a rich source of important nutrients, containing high quantities of N, S and C, which are necessary for plant growth (*McNeil et al., 2007*). Greasy raw wool is composed of protein 'keratin' with an abundance of carbon (C 50%), nitrogen (N 16- 17%) and sulphur (S 3-4%), which play an essential role in plant nutrition (*Von Bergen et al., 1963*).

Keratin is a group of insoluble, filamentous proteins, with high-sulfur content forming the bulk of epidermal appendages such as wool, claws, horns, beaks, and feathers (*Wang et al., 2016*). Keratin extracted from wool is a biopolymer with excellent properties that synthetic polymers cannot achieve (*Cardamone, 2010*).

Wool keratin has a distinct three dimensional structure and contains approximately 95% protein, 0.5% minerals, 5% lipids (*Aluigi, A., et al.2014*). Due to its low cost, biophysical stability in physiological environments, and biodegradability, previous studies focused on keratin production for biomaterials, agriculture and textile applications (*Shavandi et al., 2016; Goyal et al., 2022; Zoccola et al., 2015*). Keratin can be extracted using strong acid, alkali, high concentration of salt solutions or expensive enzymes.

Recent methods use ionic liquids for keratin extraction from wool, feathers and hair with improved yield (*Ji et al., 2016).* As compared to other reported research (*Gaidau, C et al. 2019*) we have used KOH as hydrolysis agent for its nutritional potential for plant growth.

This paper presents the method of obtaining alkaline hydrolysate from raw wool at different stages of preparation, studying if and how the hydrolysis process may be influenced by the condition of the wool.

MATERIALS AND METHODS

The raw wool was purchased from local farmers, potassium hydroxide (KOH), NH3(25% solution), Na_2CO_3 and citric acid were purchased from Silver Chemicals and the detergent was purchased from local shop.

We prepared three hydrolysate samples: sample UW- hydrolyzate from raw, unwashed wool; sample W-hydrolyzate from raw, washed wool and sample WD- hydrolysate from raw, washed, and degreased wool.

Wool washing, degreasing and hydrolysis

For sample W the raw wool was washed with tap water, mixed manually, in three one-hour sessions, until the water remained clean.

For sample WD the raw wool was washed and degreased in water in ratio 1:10 with 1% NH_3, 1% Na_2CO_3 and 1% detergent by manually stirred for three hours at 35°C.

For both samples W and WD the wool was dried in the sun in the open air. Large impurities such as straw, pieces of wood, soil, burrs, etc. were manually separated from all wool samples (Fig.1).

The alkaline hydrolysis was made in a solution containing water in ratio 1:5 and 8%KOH at room temperature for 24 hours, followed by boiling at 100°C for 1 hour, followed by filtration. The pH of the hydrolysate was adjusted by adding citric acid.

a) b) c)

Fig. 1 - a) Raw wool; b) large impurities from raw wool; c) washed wool

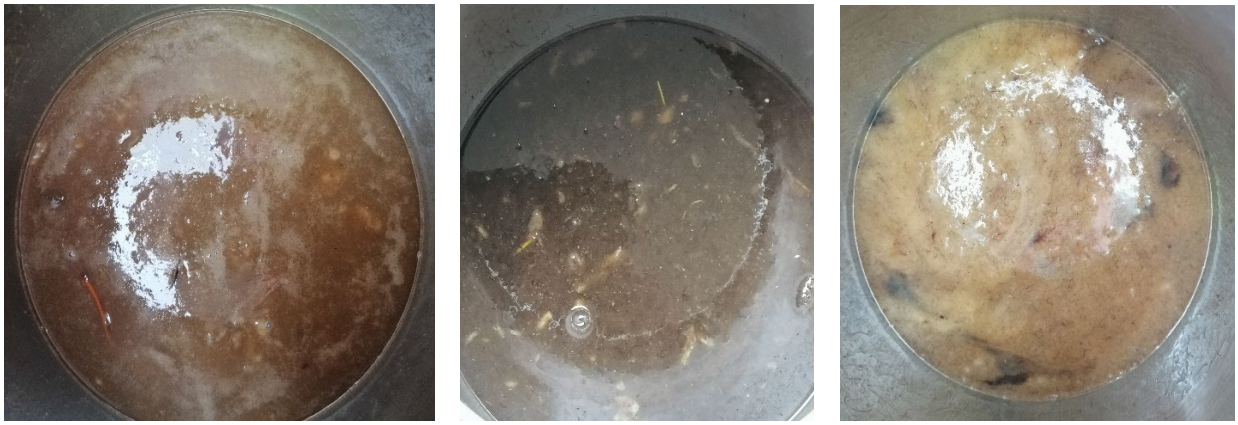
The obtained keratin hydrolysates were physically analyzed for remain impurities and dry matter. Impurities obtained after filtration were measured with a Partner precision electronic balance.

The measurable parameter determined was the dry matter content determined by heating a quantity of hydrolysate to 70°C until the liquid evaporated completely and the dry matter was measured with a Partner precision electronic balance.

RESULTS

Three keratin hydrolysates were obtained using raw wool in various stages of cleaning and degreasing, following the technological steps presented above.

The chemical action of the alkaline medium manifests itself on the wool keratin by releasing electro-valences, breaking the cystine bridge, and hydrolyzing peptide bonds under the influence of the pH value of the reaction environment, working time, and temperature *(Ifrim, 1979).*



Sample UW **Sample W** **Sample WD**

Fig. 2 - Mixture of wool with 8% KOH solution after 24 h

Table 1

Values for hydrolysed mass, impurities, and citric acid for pH adjustment

Sample	Hydrolysed mass, g	Dry Impurities g	Citric acid for pH 6.5-7 g / %
Sample UW	785	1.15	43 / 5.2%
Sample W	970	1.05	44 / 4.3%
Sample WD	980	0.49	54.7 / 5.3%

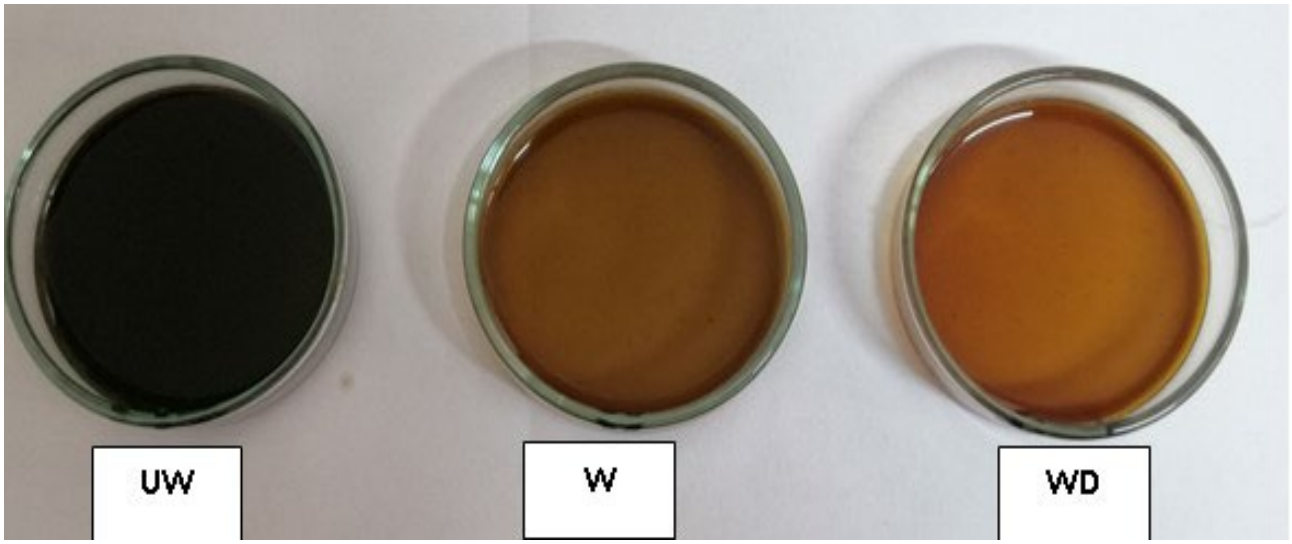


Fig. 3 - Appearance of the hydrolysate samples obtained

Analyzing the data in Table 1, we can see that the hydrolysate sample UW, obtained from unwashed wool, as expected, has the highest impurity content after hydrolysis.

The hydrolysate sample obtained from washed and degreased wool, WD, has a much lower impurity content, approximately half that of the other two samples.

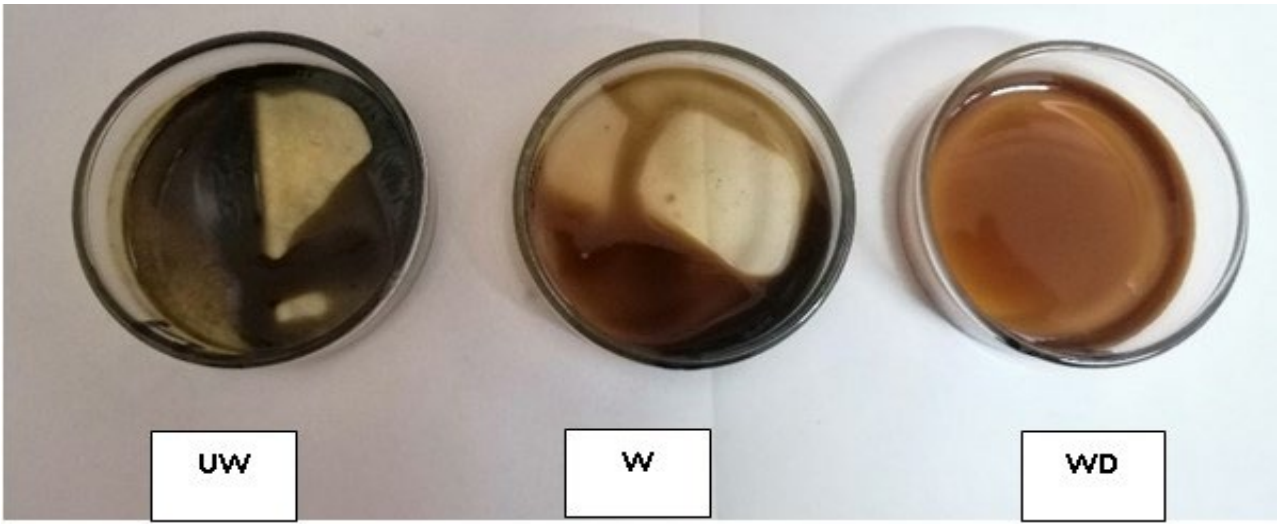


Fig. 4 - Dry matter resulting from drying the samples

Table 2

Values obtained for dry matter

Sample	Liquid phase			Dry phase	
	Vessel weight, g	Liquid weight, g	Total weight, g	Total weight, g	Dry matter, g
Sample UW	14.14	3	17.14	15.37	1.23
Sample W	14.25	3.1	17.35	15.24	0.99
Sample WD	14.74	3	17.74	15.50	0.76

The data in Table 2 confirm the results in Table 1, namely that the WD sample has the lowest dry matter content, which correlates with the lowest impurity content. This is due to the washing and degreasing process, which removes and breaks down most of the impurities in the raw wool.

CONCLUSIONS

The production of keratin hydrolysates from wool by-products is an environmentally friendly option for creating new value-added products in the category of bio-stimulants and organic fertilizers.

The results of the research showed that complete solubilization of wool can be achieved by alkaline hydrolysis with potassium hydroxide, with a concentration of 8% for raw wool in various stages of cleaning/degreasing.

It has been observed that the hydrolysate obtained from wool that has been washed and degreased beforehand in water in ratio 1:10 with 1% NH_3, 1% Na_2CO_3 and 1% detergent has the lowest content of impurities obtained after filtration - approx. 42% compared to the impurity content in the hydrolysate obtained from unwashed raw wool, and also the lowest dry matter content - approx. 60% compared to the hydrolysate obtained from unwashed raw wool.

The data obtained in this research refer only to the physical characteristics of the hydrolysate obtained from raw wool and prove that, at first glance, hydrolysate can also be obtained from unwashed raw wool using the same technology, which would lead to savings in wool washing and degreasing costs.

As a continuation of this research, the chemical characteristics of the three types of hydrolysates should be studied to verify whether the cleanliness of the wool influences the composition and chemical characteristics of the hydrolysates intended for use in agriculture.

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EFFICACY AND SELECTIVITY OF IMAZAMOX AND PENDIMETHALIN BASED HERBICIDE IN WEED CONTROL IN SOYBEAN CROPS

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EFICACITATEA ȘI SELECTIVITATEA AMESTECULUI DE IMAZAMOX ȘI PENDIMETHALIN ÎN CONTROLUL BURUIENILOR DIN CULTURILE DE SOIA

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ABSTRACT

The research was conducted in 2021, in Călărași County, in 3 experimental plots seeded with soybean and aimed to evaluate the selectivity and efficacy of the herbicide based on imazamox and pendimethalin for weed control. The experiments were placed in randomized blocks, in 4 repetitions with a plot area of 100 m^2. Weed density was assessed as number of plants/m^2 and as percentage of ground cover. Efficacy was evaluated at 14, 28 and 40 days after treatments application, being compared to the untreated control, according to the EWRS scale. Statistical data calculation was performed using the ARM-9 software (P= .05, Student-Newman-Keuls). The floristic composition of the experimental plots has been diverse, as annual species prevailed. The following species were recorded: Abutilon theophrasti, Amaranthus retroflexus, Ambrosia artemisiifolia, Cannabis ruderalis, Chenopodium album, Galium aparine, Fumaria officinalis, Hibiscus trionum, Papaver rhoeas, Polygonum spp.*, Solanum nigrum, Sonchus* spp.*, Viola arvensis and Xanthium* spp*. of dicotyledonous class and among the monocotyledonous were Setaria* spp.*, Echinochloa crus-galli and Poa annua. The treatments were applied in pre-emergence after sowing until BBCH 05 (radicle emerged from seed) at doses of 2.2, 3.4 and 4.5 l/ha. The herbicide based on Imazamox and Pendimethalin provided good efficacy in controlling annual weeds in soybean crops whereas the best results being obtained at higher doses of 4.5 l//ha. At doses of 2.2 l/ha and 3.4 l/ha, the species of Setaria, Echinochloa, Galium, Solanum, Xanthium, Sonchus, Polygonum are not controlled or are insufficiently controlled. No phytotoxicity phenomena were recorded in experimental plots.*

REZUMAT

Cercetările au fost efectuate în anul 2021, în județul Călărași în 3 loturi experimentale cultivate cu soia și au avut ca scop evaluarea selectivității și eficacității erbicidului pe bază de imazamox și pendimethalin în controlul buruienilor. Experiențele au fost amplasate în blocuri randomizate, în 4 repetiții cu suprafața parcelei de 100 m^2. Densitatea buruienilor a fost evaluată ca număr de plante/m^2 și ca procent de acoperire a solului. Eficacitatea a fost evaluată la 14, 28 și 40 de zile de la aplicarea tratamentelor, comparativ cu martorul netratat, conform scalei EWRS. Calculul statistic al rezultatelor s-a efectuat cu ajutorul software-ului ARM-9 (P= .05, Student-Newman-Keuls). Compoziția floristică a loturilor experimentale a fost diversă, dominante fiind speciile anuale. Au fost prezente următoarele specii: Abutilon theophrasti, Amaranthus retroflexus, Ambrosia artemisiifolia, Cannabis ruderalis, Chenopodium album, Galium aparine, Fumaria officinalis, Hibiscus trionum, Papaver rhoeas, Polygonum spp.*, Solanum nigrum, Sonchus* spp.*, Viola arvensis și Xanthium spp. din clasa dicotiledonate iar dintre monocotiledonate Setaria spp., Echinochloa crus-galli și Poa annua.Tratamentele au fost aplicate în premergență după semănat până la BBCH 05 (până când radicula a ieșit din sămânță) la doze de 2,2, 3,4 și 4,5 l/ha. Erbicidul pe baza de Imazamox și Pendimethalin a avut o eficacitate bună în controlul buruienilor anuale din culturile de soia, cele mai bune rezultate obținându-se la doza de 4,5 l/ha. La dozele de 2,2 l/ha și 3,4 l/ha speciile de mohor, iarba barboasă, turiță, zărnă, cornuți, susai, hrișcă nu sunt controlate sau sunt controlate insuficient. Nu s-au înregistrat fenomene de fitotoxicitate în loturile experimentale.*

INTRODUCTION

Weed control is an essential link in soybean crop technology (*Glycine max* (L.) Merril) as yield loss due to weed infestation could be between 40 și 90%, depending on type of weed, soil, seasons and weed infestation intensities (*Gogoi et al., 1991; Kachroo et al., 2003; Berca, 1996 and 2004; Sodangi et al., 2006 and 2007; Nainwal et al., 2010; Caverzan et al., 2019; Zain et al., 2020*).

Soybean plants have a particularly sensitivity to weeds, from the first days after emergence until harvest time, thus damage caused by weeds is significant, resulting in increased production costs. Once infested by weeds, especially in the early stages of growth, soybean crops cannot recover and cannot ensure best yields, even if the weeds are subsequently controlled (*Rusu et al., 2014*).

The more abundant and earlier the degree of weed infestation, the more obvious the contribution to yield decrease (*Thurlow and Buchanan, 1972; Coble et al., 1981; Baysinger and Sims, 1991; Begonia et al., 1991; Fellows and Roeth, 1992; Van-Acker et al., 1993; Senthil et al., 2009; Yadav et al., 2017*). Therefore, one of the most important aspects of soybean crop technology is weed management (*Lamptey et al., 2015; Jannink et al., 2000*).

In agricultural practice, various control methods are used collectively to effectively manage weed infestations in soybeans: preventive, cultural, mechanical, biological and chemical (*Datta et al., 2017; Song et al., 2020; Tehulie et al., 2021*). Herbicide application is the most common method for weed control in soybean crops due to its efficiency, velocity and low cost compared to other control methods.

The lack of labor force during the peak weed infestation period, the difficulty of performing mechanical hoeing due to rain, and high costs raise problems for effective weed control in soybean crops. Weed management through herbicide application remains the only applicable alternative in these situations. Herbicide treatments applied to the soil during seedbed tillage or immediately after sowing, supplemented with treatments during the growing season, can ensure weed-free soybean crops until harvest.

Taking account that soybean crop is subject to fierce competition by weeds, especially in the early stages of growth, early herbicide control is a necessity for this crop in order to achieve adequate yields and to manage weed resistance (*Kalpana and Velayutham 2004; Parmar et al., 2016; Oliveira et al., 2017; Nunes et al., 2018; Coradin et al., 2019)*. In almost all situations, the best results in weed control in soybean crop are fullfilled with combination herbicides (mixtures).

Under these circumstances, this paper provides data on efficacy of the herbicide based on imazamox and pendimethalin applied in pre-emergence to control of annual weeds in soybean crops.

MATERIAL AND METHOD

Field experiments were conducted during 2021, in 3 experimental lots cultivated with soybeans in Călărași county. The soybean crops assessed were cultivated by private farmers according to their own technologies. Agrophytotechnical data regarding experimental plots (location, soil, previous crop, plant stage BBCH, phytosanitary treatments) are written in Table 1.

Table 1

Agrophytotechnical data regarding soybean experimental plots

Location	Pelinu	Tămădău Mare	Borcea
GPS coordinates	44°27'43" N, 27°01'46" E	44°28'14" N, 26°34'23" E	44°17'791" N; 27°47'24" E
Soil	Cernoziom cambic		
Previous crop	Maize	Winter wheat	Winter barley
Variety	Procera 1020	Dakota	Ovidiu
Sowing date	07.05.2021	04.05.2021	05.05.2021
Density	55 000 pl/ha	60 000 pl/ha	60 000 pl/ha
Emergence date	21.05.20201	18.05.2021	25.05.2021
Fungicides/Insecticides	Pictor: 0.5l/ha-20.06.2021 Ercole:10 kg/ha-25.04.2021	Ridomil gold MZ: 2.5 kg/ha - 11.06.2021 Trika Expert: 12 kg/ha - 22.04.2021	Pictor -0.5l/ha 2 treatments:14.06.2021; 28.06.2021 Ortus 5 SC: 0.5 l/ha; 30.05.2021 Nissorun 10 WP:0.4 kg/ha; 14.06.2021
Treatment date	10.05.2021	11.05.2021	8.05.2021
BBCH (Growth stage)	BBCH 01*	BBCH 03**	BBCH 05***

*Beginning of seed imbibition **Seed imbibition complete ***Radicle emerged from seed

The experiments were placed in randomized blocks, in 4 repetitions, with a plot area of 100 m^2 each. A nontreated control was included for comparison. Imazamox (16.7 g/l) and Pendimethalin (250 g/l) based herbicide, formulated as CE (Emulsifiable Concentrate), was applied preemergence at doses of 2.2, 3.4 and 4.5 l/ha. Observations were focused on the determination of weed species found in the experimental fields, weed density and control effectiveness. Weeds density was assessed as percentage of soil coverage and in number of plants per square meter. Determination of segetal flora was performed on one square meter using a metric frame.

The number of weeds per square meter was determined by weed mapping with a metric frame of 1 m^2 side in 4 repetitions on the diagonal of the plot. The percentage of weed cover was assessed visually, according to species, density and phenological aspects of each weed (emerging, budding, flowering, fruiting, ripening, seed dispersal, height, etc.). The herbicide efficacy was recorded at the 14, 28 and 40 days after treatments according EWRS (European Weed Research Society) and the effectiveness was calculated in % control compared to untreated samples.

Crop phytotoxicity was assessed visually on a rating scale from 0% to 100% (0 - no injury to soybean plants and 100 - complete drying of the plants). Statistical data calculation was performed using ARM-9 software (P = .05, Student-Newman-Keuls).

RESULTS

The experimental field taken into study was infested by various annual weed species, consisting of both dicot and monocot weeds**.** Major weed flora found in the experimental field was grouped into broad leaved and grass weeds. Thus, at Pelinu, the following weed species were encountered: *Setaria* spp., *Echinochloa crus-galli*, *Galium aparine*, *Amaranthus retroflexus*, *Chenopodium album*, *Polygonum aviculare*, *Solanum nigrum* and *Abutilon theophrasti* (Table 2). The species *P. persicaria*, *Hibiscus trionum*, *Sonchus arvensis*, *Cannabis ruderalis*, and *Sorghum halepense* were also encountered, but did not raise any control problems, due to their density of <5 plants/m^2.

Annual monocotyledons (*Setaria* and *Echinochloa*) were dominant, with a weed infestation rate of 40.5% in the control sample 40 days after treatment application. Infestation with dicotyledonous species was more homogenous, with the presence of *G. aparine* (cleavers) being notable.

Under these infestation conditions, at 40 days after the application of the treatments, Imazamox and Pendimethalin based herbicide had a good efficacy in controlling annual weeds, with the best results being obtained in the Pelinu experimental plot, obviously at higher doses of 3.4 and 4.5 l/ha (Table 2).

Table 2

The efficacy of Imazamox and Pendimethalin in soybean after 40 days of treatment (Pelinu 2021)

Experimental sample	Dose l/ha	Efficacy (% control compared to untreated check)							
		SETSS	ECHCG	GALAP	AMARE	CHEAL	POLAV	SOLNI	ABUTH
% of soil coverage at untreated		22.5%	18.0%	15.5%	11.2%	14.2%	8.7%	7.7%	7.2%
Untreated		0.0b	0.0c	0.0c	0.00d	0.00d	0.0d	0.00d	0.00c
Imazamox and Pendimethalin based herbicide	2.2	52.5a	35.0b	50.0c	50.0c	50.0c	41.2c	37.5c	53.7b
	3.4	61.2a	55.0a	82.5b	82.5b	82.5b	71.2b	62.5b	72.5ab
	4.5	75.0a	68.7a	100.0a	100.0a	100.0a	90.0a	90.0a	88.7a
LSD P =.05		21.66	15.89	29.93	15.48	15.48	17.53	20.56	19.50
Standard Deviation		13.54	9.93	18.71	9.68	9.68	10.96	12.85	12.19

For *Setaria* species, we determined a weed infestation rate >22% in the control, monitoring four species of foxtail: *S. viridis*, *S. glauca*, *S. verticilata*, and *S. faberi*. The efficacy for controlling *Setaria* species was 52% at a dose of 2.2 l/ha, 61% at a dose of 3.4 l/ha, respectively 75% at a dose of 4.5 l/ha.

For barnyard grass, the efficacy did not exceed 68.7% at the maximum dose tested. For annual dicotyledonous species, the efficacy was quite good, being lower for common knotgrass, black nightshade, and velvetleaf, especially at lower doses.

The lowest efficacy in the experimental plot at Pelinu was recorded at a dose of 2.2 l/ha, being 35.0% for *Echinochloa*, 37.5% for *Solanum*, and 43.2% for *Polygonum*, with efficacy for the other species being approximately 50%.

The following species were encountered in the experimental field at Tămădău Mare: *Polygonum convolvulus* (synonym *Fallopia convolvulus*), *C. album*, *Xanthium* species, *Viola arvensis*, *Ambrosia artemisiifolia*, *Hibiscus trionum* of the dicotyledonous class, and *Poa annua* of the monocotyledonous class. Other species with a density of <5 plants/m^2 were also found: *A. retroflexus*, *Cirsium arvense*, *S. halepense*, *Convolvulus arvensis* and *E. crus-galli*. The dominant species was *P. convolvulus*, with a weed infestation rate >40% at 40 days after treatment application in the control plot (Table 3). Black bindweed is an annual flowering plant of the *Polygonaceae* family, with rapid growth, native to Europe, Asia and North Africa, and an invasive species in North America. It coils itself around crop plants and can block harvesting equipment.

The ideal temperature for seeds to germinate is 5 °C, but they can germinate at temperatures as high as 30 °C. Four to five weeks after emergence, the stems of climbing buckwheat begin to wrap around surrounding plants. During this time, the stems grow about 1-2 cm per day, and the roots branch out more and more. Two to three weeks after emergence, climbing buckwheat is very sensitive to herbicides, which is the optimal period for applying treatments. The flowering period occurs in stages from June to September, so that this weed may produce up to 200 seeds per plant.

Table 3

The efficacy of Imazamox and Pendimethalin in soybean after 40 days of treatment (Tămădău Mare 2021)

Experimental sample	Dose l/ha	Efficacy (% control compared to untreated check)							
		POLCO	CHEAL	XANSS	VIOAR	AMBEL	HIBTR	GALAP	POAAN
% of soil coverage at untreated		40.5%	20.0%	12.0%	6.7%	8.5%	8.2%	11.2%	12.5%
Untreated		0.0 c	0.0 c	0.0 c	0.00 d	0.00 b	0.0 c	0.00 c	0.00 c
Imazamox and Pendimethalin based herbicide	2.2	23.7 b	57.5 b	40.0 c	50.0 c	60.0 a	66.2 b	51.2 b	48.7 b
	3.4	47.5 a	80.0 a	67.5 b	82.5 b	73.7 a	92.5 a	68.7 b	60.0 ab
	4.5	55.0 a	88.7 a	83.7 a	100.0 a	85.0 a	100.0 a	90.0 a	78.7 a
LSD P =.05		18.29	14.61	22.47	15.48	21.16	12.38	19.86	19.27
Standard Deviation		11.43	9.13	14.05	9.68	13.72	7.73	12.41	12.04

Under these weed infestation conditions, 40 days after treatment application, the Imazamox and Pendimethalin-based herbicide showed good efficacy in controlling annual weeds in the experimental plot at Tămădău Mare, except for the black-bindweed species, for which the efficacy at 42 days was only 23.7% at a dose of 2.2 l/ha, 47.5% at a dose of 3.4 l/ha, and 55% at a dose of 4.5 l/ha, since this weed prevailed in the experimental field.

At the maximum dose tested, the mixture of iamzamox and pendimethalin had good efficacy in controlling annual weeds: 83.7% for *Xanthium* species, 85% for *Ambrosia*, 90% for *Galium* and 100% for *Viola* and *Hibiscus*. Adequate control was also recorded for the species *P. annua*, with an efficacy of 48.7% at a dose of 2.2 l/ha, 60% at a dose of 3.4 l/ha and 78.7% at a dose of 4.5 l/ha.

In the experimental field in Borcea, the following dicotyledons were encountered: *P. persicaria, G. aparine, C. album, Fumaria officinalis, Papaver rhoeas, C. ruderalis*, *Sonchus* species and among the monocotyledons, the species *E. crus-galli* (Table 4). Annual dicotyledons predominated with a weed infestation rate of approximately 76%, 40 days after treatment application in the control sample.

Table 4

The efficacy of Imazamox and Pendimethalin in soybean after 40 days of treatment (Borcea, 2021)

Experimental sample	Dose l/ha	Efficacy (% control compared to untreated check)							
		POLPE	GALAP	CHEAL	FUMOF	PAPRH	CNIRU	SONSS	ECHCG
% of soil coverage at untreated		20.5%	12.7%	10.7%	5.5%	11.2%	8.7%	7.2%	18.2%
Untreated		0.0 c	0.0 c	0.0 d	0.00 b	0.00 c	0.0 c	0.00 c	0.00 c
Imazamox and Pendimethalin based herbicide	2.2	50.0 b	35.0 b	62.5 c	60.0 a	52.5 b	37.5 c	23.7 b	32.5 b
	3.4	66.2 a	55.0 a	90.0 a	73.7 a	73.7 ab	62.5 b	47.5 a	51.2 a
	4.5	77.5 a	68.7 a	100.0 a	85.0 a	90.0 a	76.2 a	55.0 a	61.2 a
LSD P =.05		13.34	15.89	9.33	21.16	22.78	16.66	18.28	15.71
Standard Deviation		8.34	9.93	5.83	13.72	14.24	10.41	11.43	9.82

Forty days after application, the imazamox and pendimethalin based herbicide showed good efficacy in controlling annual weeds in the experimental plot in Borcea, providing effective control of *Chenopodium*, *Fumaria* and *Papaver*, and satisfactory control of *P. persicaria* and *C. ruderalis*.

The lowest efficacy was recorded for *Sonchus* species, being 23.7% at a dose of 2.2 l/ha, 47.5% at a dose of 3.4 l/ha, and 55% at a dose of 4.5 l/ha. Weeds from the *Polygonaceae* family showed differences in sensitivity, as *Polygonum convolvulus* biotypes proved to be much more resistant to the action of Imazamox and Pendimethalin-based herbicides than P. persicaria and *P. aviculare*.

For the control of cockspurgrass, the efficacy was 32.5% at a dose of 2.2 l/ha, 51.2% at a dose of 3.4 l/ha, and 61.2% at a dose of 4.5 l/ha, with results similar to those obtained at Pelinu. The mixture of imazamox and pendimethalin proved to be very effective for controlling *Chenopodium album*, which was found in all experimental plots.

Imazamox [3-pyridinecarboxylic acid, 2-[4,5-dihydro-4-methyl-4-(1-methylethyl)-5-oxo-1H-imidazol-2-yl]-5-(methoxymethyl] - is an active substance of the chemical group of imidazolinones that is easily absorbed and taken up by the roots and leaves of weeds. Imazamox acts by inhibiting the enzyme acetohydroxyacid synthase (AHAS).

This inhibition disrupts protein synthesis and subsequently stops cell growth and division due to the lack of proteins necessary for growth, ensuring weeds demise. The chemical is absorbed through the foliage and translocated through both the xylem and phloem. Imazamox also has long residual activity, ensuring reliable protection against a new wave of weeds (*Brady et al., 1998*; *Shaner and O'Connor, 1991*; *Tan et al., 2005*; *Senseman, 2007*).

Pendimethaline [N – (I ethylpropoly) – 3,4 dimethyl – 2,6– benzamine] is an organic herbicide of the dinitroaniline class used to control annual monocotyledonous and some annual dicotyledonous weeds. It inhibits both cell division and its elongation in the root meristem.

Weed development is directly stopped as a result of absorption through the coleoptile/hypocotyl growth tips. Weeds die immediately after germination or emergence, being excluded early from competition (*Cork and Krueger, 1992*; *Smith, 2004*; *Oyeleke, 2011*; *Zain et al., 2020*; *Onwuchekwa, 2023*).

The combination of the two active substances enlarged the spectrum of weeds controlled, ensured higher levels of control, and highlighted the importance of using herbicides with different modes of action, preventing the development of resistance (*Vidal et al., 2016*).

Overall, imazamox and pendimethalin based herbicides provided good protection for soybean crops against annual weeds, with results varying depending on the cultivation technologies applied by farmers, the spectrum and intensity of weed infestation and soil and climate conditions. In general, the action of the two active substances on dicotyledons was better.

Regarding the occurring of resistance, we observed that although the *G. aparine* species was present in all experimental plots, the populations in the Borcea plot proved to be the most sensitive to the action of the two active substances.

This species is a problematic weed that has become increasingly difficult to control by herbicides, being resistant to the herbicide 2.4-D+MCPA. Several populations of *G. aparine* have shown cross-resistance to ALS-inhibiting herbicides. Some populations have been found to have developed multiple resistance to both auxin and ALS herbicides (*Nosratti and Muhammadyari, 2019*; *Papapanagiotou et al., 2019*; *Babaei and Moradi, 2025*).

Furthermore, following observations and evaluations, we once again noted the influence of the previous crop on the weed species noted in the crop. Thus, in the experimental plots at Tămădău Mare and Borcea, where the previous crops were cereals, the soybean crops were infested by some weed species characteristic of these crops: *Galium, Fumaria and Papaver.* Instead, in Pelinu, where the previous crop was corn, there were weed species that are usually found in hoeing crops: *Amaranthus, Solanum, Setaria*, etc. No phytotoxicity was recorded in experimental plots *(OEPP/EPPO Standards Bulletin, 2014).*

No yellowing, browning, deformation of plants, stunting or deficiency of soybean growth and development was observed.

Aspects from experimental field are presented in Figure 1.

Fig. 1 - Aspects from experimental field

CONCLUSIONS

Floral composition of experimental plots was diverse depending on the previous crop and the growing technology applied by the farmers, the annual weed species were found dominant.

The herbicide based on imazamox and pendimethalin, applied pre-emergence, demonstrated high efficacy in controlling annual weeds across all three experimental locations (Pelinu, Tămădău Mare, Borcea).

Timing is critical – the herbicide must be applied immediately after sowing but before crop and weed emergence to prevent early competition.

Crop rotation plays an important role, as the previous crop influences the weed flora; for example, cereal crops favor the presence of *Fumaria*, *Papaver*, and *Galium* species.

The herbicide's efficacy was dose-dependent, with the best results observed at the highest tested dose (4.5 l/ha), effectively controlling problematic species such as *C. album*, *A. retroflexus*, and *G. aparine*.

Weeds from the Polygonaceae family (e.g., *P. convolvulus*) exhibited higher tolerance to treatment, especially when dominant in the field.

Integrating chemical control with cultural and mechanical methods, where possible, can enhance the effectiveness and sustainability of weed management system

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SAFFLOWER CULTIVATION: CHALLENGES AND PERSPECTIVES
/
CULTURA DE ȘOFRĂNEL: PROVOCĂRI ȘI PERSPECTIVE

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ABSTRACT
Safflower (Carthamus tinctorius L., fam. Asteraceae) is cultivated due to its high adaptability to arid regions with low rainfall. Compared to other oilseed crops (rapeseed, sunflower, soybean, etc.), it shows good tolerance to cold, which makes it suitable for cultivation in various climatic zones. Safflower is mainly grown for its seeds, from which high-quality vegetable oil is extracted, and for its flower petals, which are used as a substitute for Saffron. This paper aims to present the main challenges as well as the perspectives for this crop. The challenges include aspects such as limited knowledge related to this plant, the cultivation technology adapted to different regions, and several economic issues. The perspectives for this valuable crop consider its multifunctional uses, the high added value represented by the nutritious oil and petals, and its applications in various industries (food, cosmetics, textiles, etc.).

REZUMAT
Șofrănelul (Carthamus tinctorius L., fam. Asteraceae), este cultivat datorită adaptabilității sale ridicate la regiunile aride, cu precipitații scăzute. În comparație cu alte culturi de oleaginoase (rapiță, floarea-soarelui, soia, etc.) are o rezistență bună la frig, ceea ce îl face potrivit pentru cultivare în diverse zone climatice. Cultura de Șofrănel este predominantă pentru semințe, din care se obține un ulei vegetal de calitate și pentru petalele florilor, care sunt utilizate ca înlocuitor al Șofranului. Lucrarea își propune prezentarea principalelor provocări dar și perspectivele pentru această cultură. Provocările includ aspecte privind: cunoștințele limitate legate de această plantă, tehnologia de cultură adaptată diferitelor regiuni, dar și o serie de aspecte economice. Perspectivele acestei culturi valoroase țin cont de: utilizarea multifuncțională a acesteia, valoarea adăugată ridicată reprezentată de uleiul nutritiv și de petale, de utilizările sale în diferite industrii (alimentară, cosmetică, textilă, etc.).

INTRODUCTION

Safflower (*Carthamus tinctorius* L., fam. *Asteraceae*) is an annual herbaceous plant, native to India, cultivated for its achenes, rich in oil (37 - 42%). The cultivation of this plant is underutilized, however, it has gained attention due to its ability to grow under high temperatures, drought, and salinity conditions, as well as its potential to produce high-quality oil. Salinity and drought have negative effects by disrupting the ionic and osmotic balance of plant cells.

The stress signal is perceived by membranes and then transduced into the cell to activate stress-responsive genes (*Hussain, M. I. et al, 2016*). The plant is adaptable to various conditions and can be cultivated in semi-arid areas where other crops fail, which makes it even more attractive for cultivation in the context of water scarcity and the challenges related to global warming (*Erbas and Mutlucan, 2023*).

The plant grows alongside wheat and barley in temperate regions, but it develops slowly during periods with short and cold days, while being tolerant to low temperatures (up to frost), with resistance varying among species varieties. Safflower is a long-day plant, requiring a photoperiod of 14 hours. It is intolerant to shade and weed infestation, with good tolerance to salts similar to cotton, but lower than that of barley. It develops well on loamy soils with high water-holding capacity, although heavy sandy soils are also suitable for safflower. It can be successfully introduced in crop rotation immediately after rice, as the soil remains saturated in depth with water resulting from rice irrigation. Safflower is recommended for cultivation in areas where the average annual precipitation is below 430 mm (*Askın and Erbas, 2020*). Regarding

moisture, in the early growth stages safflower is tolerant to high humidity and frequent rainfall. However, after flowering, a period of persistent rain and fog may facilitate infection with *Botrytis* (no resistant varieties are available). Excessive humidity can also facilitate the occurrence of alternaria leaf spot. Safflower grows optimally in regions with rainy and warm springs, followed by long, dry summers. Strong winds do not damage the yield, as the seeds are very resistant to shattering.

Safflower is generally able to withstand temperatures of -4 °C, although some lines tolerate field conditions as low as -7 °C. Experimentally, seeds buried at 10 cm depth resisted a two-week freezing period at -24 °C. During summer, temperatures of 43 °C do not pose problems for safflower, even under prolonged drought conditions. However, young plants, just at the beginning of vegetation, are sensitive to sudden temperature fluctuations, and subzero temperatures affect them. Increased humidity is required at this stage, when plants are also highly sensitive to weed competition.

The plant presents a series of economic benefits: due to its high content of oleic acid and linoleic acid, safflower oil is considered to be of high quality. The oil cakes obtained after oil extraction have a high protein content and are used in animal feed. The oil extracted from safflower seeds has a growing market demand, due to its applications in the food, pharmaceutical, and cosmetic industries, being an oil with high added value.

The flowers are used for obtaining food colorants or in the pharmaceutical industry, as the petals are rich in chalcone-type pigments (yellow and red), with applications in the food, textile, cosmetic, and pharmaceutical industries. Therefore, the plant is of particular interest as an alternative source that could ensure the production of food colorants. Recent studies (*Savcenco A., 2024*) have shown that there are problems in the use of synthetic colorants, and their consumption negatively affects the health status of the population, raising concerns regarding food safety.

The disadvantage of using synthetic colorants lies in their toxicological properties, since being synthetically produced, many of them contain residues of toxic elements (Pb, As, Cu, Cd, Se, U, Hg) or organic compounds (solvents, aromatic hydrocarbons, etc.).

In our country, the plant is included among the species with a “large biodiversity portfolio,” but it remains underutilized for commercial cultivation. Safflower offers a viable agricultural alternative to sunflower cultivation, being well adapted to growth on marginal lands. Its tolerance to water availability differentiates safflower from other oilseed species (such as sunflower and especially rapeseed), which require a constant water supply (*Ivan and Tudora, 2014; Nasiyev et al., 2022*).

Although the crop is less demanding in terms of soil quality and performs well on poorer soils and in humid areas, the plant is still not cultivated and valorized to the same extent as sunflower. Since this species is naturally well adapted to dry and warm conditions, it can be cultivated in the southern and south-eastern regions of the country. It is worth mentioning that within the “*biodiversity heritage*” of Romania, the “*wild relative*” of cultivated safflower, *Carthamus lanatus* L., can be found in spontaneous flora. Safflower is a crop with agricultural and economic potential, but it requires careful consideration of the challenges and appropriate management in order to fully exploit its perspectives, especially in the context of climate change and the continuously increasing demand for natural products.

To maximize the benefits of this crop, a strategic approach is needed, taking into account local conditions and new cultivation technologies, with the aim of improving disease resistance, adaptation to climatic conditions, and crop yield. Despite the fact that safflower could become a valuable plant for the country’s agriculture and economy, domestic studies on the chemical composition of different parts of the plant and on processing methods into commercial products have not yet been carried out.

MATERIALS AND METHODS

Under the climatic conditions of our country, safflower is sown early in spring, at the beginning of march, after completing soil preparation works (plowing, harrowing, and leveling). For sowing, the soil should be moist (down to a depth of 10 cm), with a minimum temperature of 4 °C. Any seed drill for small grains can be used for sowing, and if necessary, the seeds may be mixed with sand or sawdust to ensure homogeneous distribution in the field, after which they are incorporated into the soil at a depth of 2.5 - 5 cm.

The seeding rate is 23 kg/ha (with a density of 6 - 7 plants/m²) under non-irrigated conditions, and between 23 - 27 kg/ha (with a density of up to 10 plants/m²) under irrigation systems. Fertilization requirements depend on the soil. When cultivated on poor soils or under irrigated conditions, it is advisable to apply nitrogen fertilizers (urea 135 kg/ha). Crop maintenance consists of harrowing, carried out across the rows immediately after plant emergence. The safflower crop is parasitized by many weeds (*Orobanche* sp.,

Striga sp., etc.); among viral diseases, it is attacked by *Chilli mosaic* virus and *Cucumber mosaic* virus, while among bacterial diseases, by *Pseudomonas solanacearum*. In our country, *Zamfirescu, N., et al.* describe safflower rust, caused by the fungus *Puccinia carthami*, as a frequent disease, manifesting at different stages of plant development. The disease appears on leaves in the form of small brown-silver pustules. These begin to dry out, and the plants cease growing. Control measures include rational crop rotations, destruction of infected plants, and deep plowing. Among insects, the darkling beetle (*Opatrum sabulosum*) attacks safflower crops. This coleopteran appears in spring, feeding on the edges of cotyledons and later damaging the stems. In crop rotation, safflower can be introduced after barley or rice, as well as after other cereals. When sown immediately after rice, in addition to nitrogen fertilizers it is advisable to apply phosphorus fertilizers (19 - 34 kg/ha), placed near the seeds rather than broadcast, since phosphorus has low mobility in the soil. Crop rotation is mandatory, as the risk of disease occurrence is high.

According to some authors (*Baltensperger, D., et al., 2002*), it is also recommended to implement a fallow period on the same plot immediately after safflower cultivation, since it is considered that due to the plant residue left on the field after harvest and the high extraction capacity of the root system, the soil may become depleted. Other researchers (*Zamfirescu, N., et al., 1958*) do not mention such a negative impact of safflower cultivation on subsequent crops grown on the same plot. It is recommended that safflower should not alternate on the same plot with mustard, sunflower, or beans, due to the increased risk of *Sclerotinia* sp. occurrence. Safflower reaches maturity 110 - 150 days after sowing, and harvesting is carried out when the leaves are dry. An advantage of this crop is that it does not shatter its seeds, nor are they eaten by birds. These are two of the reasons why *Bîlteanu, Gh., et al., 1991*, recommended its cultivation in Romania.

Harvesting is done mechanically with a combine; the cylinder speed should be set at 550 rpm, and the forward speed should be 25% faster than the ground speed. For storage, the maximum allowable moisture content in silos is 8%. The oil percentage for a premium seed stock is at least 34 - 36%. No foreign matter is accepted. Yields range from 800 to 4000 kg/ha.

RESULTS

At the global level, the cultivated area of safflower in 2023 (Fig. 1) was 910,848 ha (*FAOSTAT, 2023*), with an estimated global production of 723,874.9 t (*FAOSTAT, 2023*). The global production of safflower oil in 2022 was 75,060.94 t (Fig. 2).

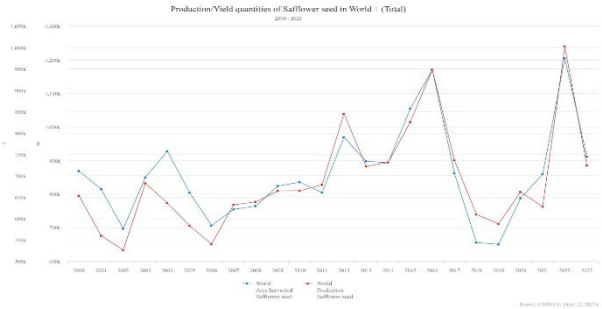

Fig. 1 - Production and yield of safflower seed worldwide (2000-2023)

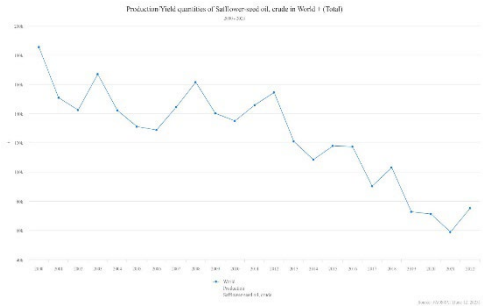

Fig. 2 - Production and yield of crude safflower seed oil worldwide (2000-2023)

With regard to safflower seed and oil production, distributed across the world regions, these are presented in Figures 3 and 4.

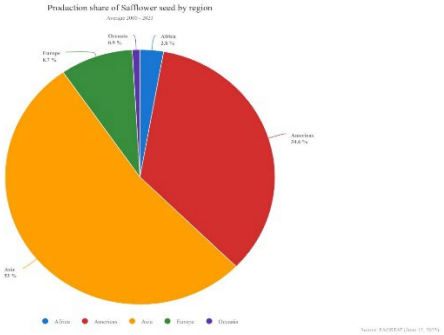

Fig. 3 - Regional production share of safflower seed *(FAOSTAT, 2023)*

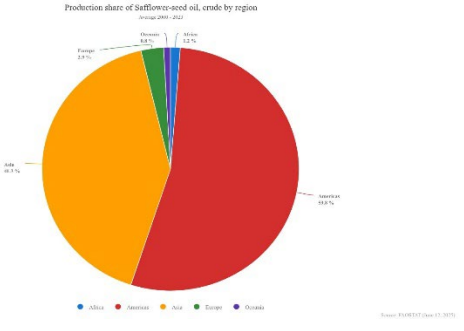

Fig. 4 - Regional production share of crude safflower seed oil (2000-2023)

According to FAO data, the regional distribution of total seed production (Fig. 3) was as follows: Asia with 363,635.2 t, representing 53% of total seed production; America with 237,281.4 t (34.6%); Europe with 59,785.48 t (8.7%); Africa with 19,287.02 t (2.8%); and Oceania with 6,018.27 t (0.9%).

Similarly, the situation regarding safflower oil production by region (Fig. 4) is as follows: America with 66,931.29 t, representing 53.8% of total oil production, followed by Asia with 51,404.15 t (41.3%); Europe with 3,561.96 t (2.9%); Africa with 1,512.99 t (1.2%); and Oceania with 1,049.66 t (0.8%).

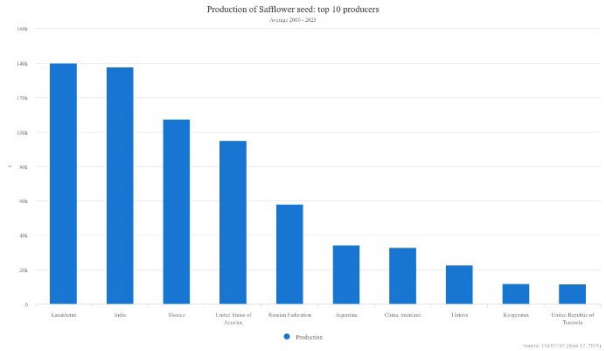

Fig. 5 - Top 10 safflower seed producers *(FAOSTAT, 2023)*

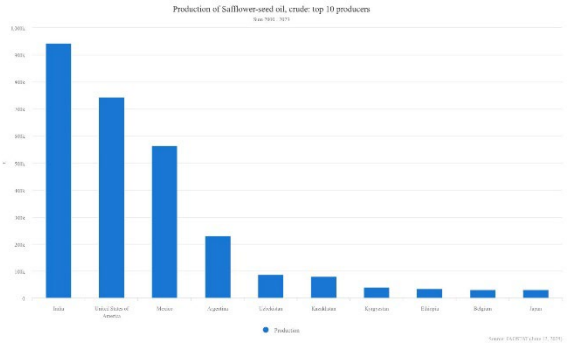

Fig. 6 - Top 10 crude safflower seed oil producers (2000-2023)

The ranking of the top 10 safflower seed-producing countries is presented in Figure 5 and is as follows: Kazakhstan with a seed production of 140,000.8 t, followed by India with 137,735.5 t, and Mexico with 107,476.4 t. The ranking is completed by the USA (95,088.75 t), Russia (58,058.82 t), Argentina (34,270.42 t), China (32,724.74 t), and Turkey (22,625.13 t). In Turkey, according to the study conducted by *Akgun, M.,and Soylemez, E.* in *2022*, it is projected that in the following five years (2022–2026), the cultivated areas of safflower as well as the annual seed quantities will decrease, on average by 515 t, while producer prices will increase by 20% per year.

Nevertheless, production yield is expected to increase by 2.5% by the end of the five-year period. As possible solutions to prevent the decrease of safflower cultivated areas and to increase production, the authors recommend providing purchase guarantees for producers, supporting entrepreneurs, and conducting studies on modern cultivation practices, marketing, and promotion.

At the global level, the top 10 safflower oil-producing countries (Fig. 6) are: India with 41,043.48 t, followed by the USA with 32,353.91 t, and Mexico with 24,556.33 t. The ranking of safflower oil-producing countries is completed by Argentina (10,021.05 t), Kyrgyzstan (4,918.91 t), Japan (3,912.5 t), Uzbekistan (3,754.57 t), Kazakhstan (3,504.09 t), Ethiopia (1,506.68 t), and Belgium (1,368.48 t). General market estimates, according to market reports (e.g., Market Research Future, IMARC), show that the global safflower oil market is valued at over USD 300 million, with an estimated annual growth rate of between 5-7%. Demand is concentrated in the USA, India, China, and EU countries (Germany, France, the Netherlands). The price is variable on international markets and depends on quality, origin, and processing methods.

The Situation in Romania - The interest in drought-resistant crops in the context of climate change brings safflower into the focus of both European and Romanian farmers. The crop is still relatively little known and not widely used, which provides an advantage. Romania has favorable soil and climatic conditions for safflower cultivation (continental, drought-prone zone). In the country, safflower is cultivated on small areas, mainly in plains and hilly regions where climatic conditions are favorable. Precise data on cultivated areas and annual production are not centralized at the national level, but interest in this crop has increased due to demand from the food, cosmetic, and pharmaceutical industries. In Romania, the price of dried flowers may vary between 100 and 200 lei/kg, depending on quality and demand.

Development Perspectives - In Romania, there is a growing interest in crop diversification and in harnessing the economic potential of safflower. Support from authorities and agricultural organizations can stimulate the development of this crop, contributing to increased farmers' incomes and to the promotion of a sustainable agricultural model.

The market potential of safflower ("false saffron") is increasing globally, due to its multiple applications in industries such as food, cosmetics, alternative medicine, and biofuels. There is also an export potential toward Western European markets, where the demand for natural ingredients is higher. However, at the national level, there are several *challenges* related to:

- a still undeveloped local market, requiring the promotion and education of both consumers and processors;
- the lack of seed processing infrastructure for oil extraction in Romania;
- difficult access to external markets without certifications (e.g., BIO, Fair Trade).

The challenges include cultivation for oil, natural colorant, and medicinal properties, as well as drought resistance, resistance to diseases and pests, competition with other crops, and adaptation to various climatic conditions. The perspectives are based on its nutritious oil and its diverse uses in the food and cosmetic industries.

The *challenges* faced by safflower cultivation include:

Climate and soil – The plant is drought-tolerant, but this may affect yield in certain regions, particularly during prolonged drought periods. It requires a warm and dry climate, but is sensitive in the germination stage. Soil quality (it prefers well-drained soils) significantly influences yield. Although drought-tolerant, safflower can be sensitive to extreme temperatures, and the selection of suitable varieties for different climatic zones may be difficult. Competition with other crops – Safflower may compete with other crops, especially in areas with low-quality soils, requiring proper soil and weed management.

Pesticide-related concerns (susceptibility to diseases and pests) – Safflower is vulnerable to various diseases and pests (mold, fusarium, rust, aphids, etc.), which can lead to yield losses and additional costs for treatments, with a negative environmental impact. Cultivation technology – There is a need for technologies adapted to temperate zones, and to maximize crop yield it is necessary to apply appropriate cultivation techniques (irrigation during critical periods, fertilization, etc.), as well as the use of specialized seed drills and harvesting equipment.

The harvesting process can be more complex and labor-intensive compared to other crops, and in some case it is carried out manually. Another challenge is the lack of certified, high-quality seeds available on the market. Economic aspect – Production costs may be higher in the case of safflower cultivation, and the selling price of products can fluctuate. Harvesting costs are also higher compared to other oilseed crops, while the marketing network remains underdeveloped, especially in Eastern Europe. The fluctuating market price of safflower oil may be volatile due to international supply and demand, and profitability can be affected by price fluctuations. Promotion and development of short supply chains are required.

Limited knowledge related to this plant – There is a lack of research and in-depth studies (investments in agricultural research), insufficient support through agricultural policies, and limited development of processing and value chains, while farmers are not familiar with the advantages and cultivation practices.

The *perspectives* for this valuable plant are as follows:

Sustainability and durability – The crop is drought-resistant, making it ideal for sustainable agriculture, representing a viable alternative to sunflower cultivation in areas affected by climate change.

Integration into organic agriculture – The plant can be cultivated in organic farming systems, without the intensive use of pesticides and chemical fertilizers, which attracts consumers concerned with health and the environment. It requires less water compared to other crops, being suitable for semi-arid regions. Moreover, it can be included in diverse crop rotations, improving soil fertility.

Economic potential of this crop – The global demand for natural and organic products is increasing, creating opportunities for the development of niche products (cold-pressed oil, natural colorants, dietary supplements). From safflower flowers, products based on natural colorants (carthamin) or dietary supplements can be obtained, which may provide farmers with additional income. High added value – The growing demand for safflower oil, considered healthier than other vegetable oils due to its high content of unsaturated fatty acids, rich in linoleic acid (Omega-6) and conjugated linoleic acid (CLA), contributes to its use in various food products (margarine, cooking oils, dietary supplements, etc.).

It is also used in the cosmetic industry, where oil extracted from safflower seeds is an ingredient in creams, lotions, and other cosmetic products (skin and hair care), due to its moisturizing, emollient, and antioxidant properties.

Competition with other crops – In some regions, farmers may choose to cultivate traditional, more profitable plants (sunflower, soybean), which can reduce the land available for safflower cultivation.

Establishment of crops for obtaining a natural colorant – From safflower flowers, a natural colorant (carthamin) is obtained, used in the food and textile industries as an alternative to synthetic colorants.

Medicinal properties – Safflower flowers have vasodilatory, antioxidant, anti-inflammatory, and anti-aggregating properties, being used in the treatment of cardiovascular diseases, hypertension, and rheumatic pain.

Uses in the textile industry – Safflower oil can be used in the production of certain types of varnishes and paints, as well as in the textile industry.

Feed and biomass – Residues can be used in animal feed or for the production of biofuels.

Price fluctuations on external markets – Safflower cultivation depends heavily on external markets (especially for oil), and global price fluctuations or a decrease in demand may endanger the profitability of the crop.

Supply chain issues – Although demand is increasing, in some regions there may be a lack of infrastructure necessary for the processing and distribution of safflower oil, which can lead to economic losses.

CONCLUSIONS

Safflower cultivation can represent a profitable and environmentally friendly opportunity, considering its advantages under drought conditions and the increasing demand for derived products obtained from this plant. However, in order to harness this potential, farmers must take into account the risks related to diseases, pests, and market instability. The implementation of modern agricultural practices and the use of appropriate technologies can contribute to the long-term success of this crop.

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AERODYNAMIC RESPONSE OF PEPPER SEEDS TO VARYING MOISTURE LEVELS: A BASIS FOR OPTIMIZING PNEUMATIC HANDLING AND SEED DISPERSAL

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BIBER TOHUMLARININ DEĞIŞEN NEM SEVIYELERINE AERODINAMIK TEPKISI: PNÖMATIK TAŞIMA VE TOHUM DAĞITIMINI OPTIMIZE ETMEK İÇIN BIR TEMEL

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ABSTRACT

This study investigates the effect of moisture content on the aerodynamic properties of pepper (Capsicum spp.) seeds to improve seed processing and transportation efficiency in agricultural operations. The experiments were conducted at four different moisture levels (5.4%, 8.6%, 12.1%, and 15.4%) and analyzed using a data set consisting of 100 pepper seeds in terms of drag coefficient, terminal velocity, lift coefficient, Reynolds number, projected area, mass, bulk density, and shape factor. The measurements of aerodynamic properties were carried out under controlled conditions and the data were evaluated by one-way ANOVA and Duncan test to evaluate the differences among moisture levels. The results revealed that moisture significantly affected the mass, bulk density, drag coefficient and final velocity, while higher moisture increased the mass and density, decreased the drag coefficient and increased the terminal velocity, probably due to changing surface roughness and water absorption. In contrast, lift coefficient, Reynolds number, surface area and shape factor remained constant, indicating consistent seed geometry and airflow properties. These findings highlight the critical role of moisture in regulating the physical and aerodynamic behavior of the seed, providing insights to optimize seed processing, storage, and pneumatic separation processes. By explaining moisture-driven changes, this study supports the development of specialized seed technologies that increase agricultural productivity and sustainability under diverse climatic conditions.

ÖZET

Bu çalışmada, tarımsal işlemlerde tohum işleme ve taşıma verimliliğini artırmak amacıyla, nem içeriğinin biber (Capsicum spp.) tohumlarının aerodinamik özellikleri üzerindeki etkisi araştırılmıştır. Deneyler dört farklı nem seviyesinde (%5,4, %8,6, %12,1 ve %15,4) yürütülmüş ve 100 biber tohumundan oluşan bir veri seti kullanılarak; sürükleme katsayısı, terminal hız, kaldırma katsayısı, Reynolds sayısı, yansıtılmış alan, kütle, yığın yoğunluğu ve şekil faktörü açısından analiz gerçekleştirilmiştir. Aerodinamik özelliklerin ölçümleri kontrollü koşullar altında yapılmış ve veriler, nem seviyeleri arasındaki farklılıkları değerlendirmek amacıyla tek yönlü ANOVA ve Duncan testi ile analiz edilmiştir. Sonuçlar; nemin kütle, yığın yoğunluğu, sürükleme katsayısı ve terminal hızı anlamlı düzeyde etkilediğini, daha yüksek nemin kütle ve yoğunluğu artırırken, sürükleme katsayısını azalttığını ve muhtemelen yüzey pürüzlülüğü ile su emilimindeki değişikliklerden dolayı terminal hızı artırdığını ortaya koymuştur. Buna karşılık; kaldırma katsayısı, Reynolds sayısı, yüzey alanı ve şekil faktörü sabit kalmış, bu da tohum geometrisi ve hava akışı özelliklerinin tutarlılığını göstermiştir. Elde edilen bulgular, tohumun fiziksel ve aerodinamik davranışını düzenlemede nemin kritik rolünü vurgulamakta; tohum işleme, depolama ve pnömatik ayırma süreçlerini optimize etmek için önemli içgörüler sunmaktadır. Bu çalışma, nem kaynaklı değişiklikleri açıklayarak, farklı iklim koşullarında tarımsal üretkenlik ve sürdürülebilirliği artırmaya yönelik özel tohum teknolojilerinin geliştirilmesine katkı sağlamaktadır.

INTRODUCTION

The assessment of the physical and engineering attributes of agricultural crops is of paramount significance for the optimization of design parameters pertaining to agricultural machinery and equipment utilized in the processes of production, handling, and storage. Consequently, it is imperative to establish a comprehensive database encompassing the aerodynamic and mechanical characteristics of such products,

as these attributes are crucial in the design and development of specialized machines and their operational functionalities, including sorting, separating, and cleaning *(Kabas and Özmerzi, 2018).*

The understanding of aerodynamic behavior such as the parameters of drag force, terminal velocity, drag coefficient, and Reynolds number is crucial for operations related to the movement of air, such as pneumatic conveying, separation, cleaning, harvesting, and the drying of agricultural commodities.

The terminal velocity at the top of which particles are suspended due to a stationary vertical airflow can be measured through several testing methods. These methods consist of the free-fall, air tunnel, and elutriation techniques *(Mohsenin, N.N. 1980; Grift, T.E. et al, 1997).*

The terminal velocity of grains can be calculated from both the empirical laboratory studies and the theoretical formulas. Various ways have been devised to estimate the theoretical terminal velocity of grains *(Gorial and O'Callaghan, 1990; Song and Litchfield, 1991).* When pneumatically conveying and separating different particles in an air stream, the particle behavior is significantly affected by their aerodynamics.

During relative motion between air and materials, the aerodynamic forces acting vary in accordance with the different particles. In a vertical air stream, particle separation is achievable if only a range of particle sizes is there such that the lighter materials are carried along with the air stream and the heavy ones fall off.

When an air stream is the technology used for separating a product like lentil seed from its related matters, for example straw and chaff, it is required to have the idea about the aerodynamic characteristics of all the particles involved.

This will determine the suitable air velocities for the efficient separation of the grain from the foreign materials. As a result, the terminal velocity of the particles has been adopted as a key aerodynamic characteristic for materials during pneumatic conveying and separation from foreign materials *(Mohsenin, N.N. 1980).*

Researchers have previously conducted various studies to determine the aerodynamic properties of different cereals and seeds. *Abubakar, A.J. et al. (2019)* developed a measuring device to determine the terminal velocities of rice, sorghum and bean grains; the values of 6.95 ± 0.37 m/s, 4.71 ± 0.24 m/s and 10.98 ± 0.27 m/s were obtained, respectively.

It is known that moisture content directly and positively affects grain terminal velocity; this has also been observed in crambe *(Cardoso Neto, S.R. et al, 2020)* and cereal sorghum *(Rodrigues, G.B. et al, 2019).* However, there is limited information on this subject for quinoa.

Badr and Eissa (2018) determined the terminal velocity of quinoa grains at only 11.6% moisture content and reported high variability in sphericity, geometric diameter and surface area values. *Ibrahim, M.M. et al. (2023)* stated that no significant change was observed in the physical properties of palm pollen grains in the 4–7% moisture range, but aerodynamic properties, especially the Reynolds number ranging from 0.29–0.42 and the average terminal speed of 0.6 m/s, made significant contributions to increasing the efficiency of pollination machines. *Caetano, J.M. et al. (2022) examined* the aerodynamic properties of two quinoa varieties in the 12.1–19.5% moisture range; they determined that the terminal speed varied between 2.57–3.26 m/s, the drag coefficient varied between 1.42–2.77, and the moisture content positively affected the Reynolds number.

The aim of this study is to investigate the physical and aerodynamic properties of bell pepper seeds in detail depending on different moisture contents (5.4%, 8.6%, 12.1% and 15.4%). In this context, the drag coefficient, terminal velocity, lift coefficient, Reynolds number, surface area, mass, bulk density and shape factor of the seeds were determined, the effect of moisture content on these parameters was evaluated and the usability of the obtained data in the design and optimization of agricultural mechanization systems was revealed.

MATERIALS AND METHODS

The experiments were carried out in the laboratories of Akdeniz University Technical Sciences Vocational School. The bell pepper seeds used in the study were obtained from "Balo" type bell peppers grown in producer greenhouses in the Antalya region. 100 seeds were randomly selected from these peppers and numbered to prevent repetition of measurements (Figure 1).

After the seeds were obtained, they were stored in plastic bags at 5 ± 1 °C for seven days until the beginning of the experiment in order to preserve their original characteristics. In addition, the seed samples were manually cleaned using a sieve to remove foreign substances and then mixed to obtain a homogeneous structure.

Fig. 1 - "Balo" bell pepper seeds

The dry mass was obtained by the preparation of the samples before the addition of the water content suggested *(Vilche, C. et al, 2003).* The quantity of water added to the samples using a manual spray and calculated based on the initial moisture content.

The samples returned to the plastic bags and were kept under 4 ± 1 °C for eight days to achieve moisture equilibrium, *according to Caetano, J.M. et al. (2022).* The moisture contents established for this study were: 5.4%, 8.6%, 12.1% and 15.4% %d.b. The drying method was used to measure the moisture content of the grains, which was done for 24 hours at 105 °C in a hot air oven. In accordance with the guidelines of Seed Analysis, this process was carried out three times *(Jimoh, K.A. et al., 2023*).

The ratio of a single grain mass to its volume was used to calculate the bulk density (ρ_p, kg m^{-3}). Grain volume was computed as the product of grain thickness and surface area, as suggested by *Mohsenin, N.N. (1980), Kabas, O. et al. (2007) and Singh, S.K. et al, (2021).* A digital calliper with a resolution of 0.01 mm was used to measure the length, width and thickness of the grain.

Each sample had four replications and consisted of 100 randomly selected grains for each moisture content value. The grains were weighed on a digital scale with a precision of 0.001 g prior to the measurements of dimensions. The weight was divided by the number of grains to determine the unitary grain mass indirectly.

The projection area (A_p) of the pepper seeds was determined using ImageJ (NIH, USA) software. Digital images of the seeds placed on the surface taken from a vertical angle were analysed. Scale reference was used for calibration, and the projection area (mm^2) was automatically calculated by determining the seed contours with the thresholding method *(Ermiş, S. et al, 2025).*

A radial fan powered by a 1.5 kW electric motor was used to create the air flow. The air generated by this fan is transmitted to the pressure chamber with dimensions of 600 x 600 x 400 mm through a 200 mm diameter channel. To examine the movement of the material in the air, a transparent test channel with a diameter of 80 mm was placed in the air outlet channel and experiments were carried out using the air channel equipped with a grid that homogenizes the air flow (Figure 2).

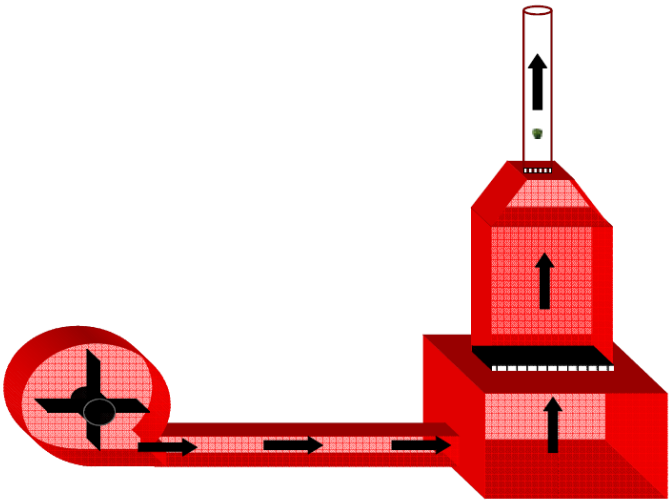

Fig. 2 - Layout of the equipment used to determine experimentally terminal velocity of pepper seeds

For the terminal velocity determination, a randomly selected pepper seed sample was placed in the center of the grid. The air flow was gradually increased until the product began to float. When the lowest rotational motion of the grains was obtained, the air velocity was measured using a digital anemometer centered at the top of the column.

The friction coefficient was calculated using the following equation, which was obtained using the terminal speed equation of *Mohsenin, N.N. (1980) and Kabas and Ozmerzi (2018).*

$$C=(2.m.g.(\rho_p-\rho_f)) / (V.\rho_p.\rho_f.A_p) \quad (1)$$

where: C is the drag coefficient (dimensionless), m is the grain mass (kg), g is the gravity acceleration (9.81 m s^{-2}), ρp is the grain density (kg m^{-3}), ρf is the air density (1.293 kg m^{-3}), V is the terminal velocity (m s^{-1}), and A_p is the grain projected area, normal to its movement in relation to the fluid (m^2). The Reynolds number was calculated using the following equation, which also includes the terminal velocity *(Mohsenin, N.N. 1980; Gojiya, D. et al., 2023).*

$$R_e=(V.D_g.\rho_f) / \mu \quad (2)$$

where: R_e is the Reynolds number (dimensionless), ρ_f is the air density (1.293 kg m^{-3}), V is the terminal velocity (m s^{-1}), D_g is the grain average geometric diameter (m), and μ is the air viscosity ($1.816.10^{-5}$ N s m^{-2}, by 20°C).

The lift coefficient was determined in a wind tunnel at 25°C with airflow velocities of 2–5 m s^{-1} *(Shaha and Pachapuri 2015).*

$$Cl=F_L / (1/2\ \rho_f.V^2.A_p) \quad (3)$$

The lift force (F_L) was calculated indirectly using the relationship F_L=m.g.sinθ where m is the seed mass (measured gravimetrically), g is gravitational acceleration (9.81 m s^{-2}), and θ is the angle of seed orientation relative to airflow, determined from high-resolution digital images (12 MP, 0.1 mm/pixel) captured during suspension in the wind tunnel. Air density (ρ_p) was set at 1.293 kg m^{-3}, airflow velocity (V) was controlled, and the seed's projected surface area (A_p) perpendicular to airflow was measured using ImageJ software.

To assess seed geometry, shape factors (SF) was calculated using the following method and equations (Kaliniewicz, Z. et al. 2022). Seeds were photographed using a high-resolution digital camera (12 MP, 0.1 mm/pixel) against a calibrated grid.

$$SF=d_e/d_{max} \quad (4)$$

The equivalent spherical diameter (d_e) was determined to represent the diameter of a sphere with the same volume as the seed, providing a standardized measure of seed size for aerodynamic comparisons.

$$d_e=\sqrt[3]{(6V/\pi)} \quad (5)$$

Images were processed with ImageJ software to measure the maximum diameter (d_{max}), defined as the longest linear dimension across the seed's surface. The equivalent spherical diameter (d_e) was determined to represent the diameter of a sphere with the same volume as the seed, providing a standardized measure of seed size for aerodynamic comparisons. Seed volume (V) was estimated by dividing the gravimetrically measured seed mass (m) by the bulk density (ρ_b), both obtained from direct measurements (mass via precision balance, ±0.01 mg; density via volumetric displacement).

All data obtained were statistically analysed using variance analysis (ANOVA) to examine differences between groups. Duncan's multiple comparison test was used to determine text.

RESULTS

Table 1 shows the mean values and standard deviations of the aerodynamic properties of pepper seeds at four different moisture levels (5.4%, 8.6%, 12.1%, 15.4%).text.

Table 1

Summary statistics: Mean and standard deviation by moisture level

Parameters	5.4%		8.6%,		12.1%		15.4%	
	Mean	Std	Mean	Std	Mean	Std	Mean	Std
Drag Coefficient	0.475	0.021	0.445	0.020	0.415	0.019	0.387	0.018
Terminal Velocity (m	2.50	0.09	2.63	0.09	2.74	0.08	2.83	0.08
Lift Coefficient	0.278	0.005	0.279	0.005	0.281	0.005	0.283	0.005
Reynolds Number	996.35	10.21	991.47	10.19	1000.24	10.31	1014.60	10.42
Surface Area (mm²)	10.23	0.25	10.05	0.24	10.29	0.25	10.15	0.24
Mass (mg)	4.56	0.13	4.86	0.14	5.37	0.15	5.87	0.16
Bulk Density (kg m-	1216.38	25.08	1260.77	26.11	1356.65	27.23	1444.75	28.06
Shape Factor	0.863	0.008	0.860	0.008	0.855	0.008	0.858	0.008

As given in Table 1, with higher humidity there is an increase in mean values for Mass (from 4.56 mg to 5.87 mg) and mean values for Density (from 1216.38 kg m^{-3} to 1444.75 kg m^{-3}). This reflects water absorption, and the standard deviations show moderate variability (0.13–0.16 mg for Mass, 25.08 – 28.6 kg m^3 for density). While drag coefficient decreases with moisture content terminal velocity increases. Lift coefficient and shape factor show low variability (S.D 0.005–0.008), indicating stability.

Table 2 shows the F and p values obtained from the one-way ANOVA test testing significant differences among humidity levels for each parameter.

Table 2

Analysis of variance (ANOVA) on the effects of different moisture contents on pepper seed aerodynamic properties

Parameters	F-Statistic	P-Value
Drag Coefficient	56.78	<0.05
Terminal Velocity (m	53.24	<0.05
Lift Coefficient	0.12	>0.05
Reynolds Number	1.45	>0.05
Surface Area (mm²)	1.67	>0.05
Mass (mg)	302.45	<0.05
Bulk Density (kg m^{-3})	298.67	<0.05
Shape Factor	0.34	>0.05

One-way ANOVA was conducted with 100 observations per level (total N = 400, df_between = 3, df_within = 396) to assess whether the means of each aerodynamic parameter were significantly different across four moisture levels (5.4%, 8.6%, 12.1% 15.4%). The ANOVA for the drag coefficient (Cd) yielded an F-value of 56.78 with a p-value less than 0.05, indicating significant differences in the drag coefficient across moisture levels. This suggests that moisture content affects air resistance during fall by changing the surface properties of the seed. Similarly, terminal velocity (m/s) showed a significant result with an F-value of 53.24 ($p < 0.05$), indicating that the speed at which seeds reach terminal fall velocity varies with moisture, probably due to changes in mass or shape. In contrast, the lift coefficient (Cl) had an F-value of 0.12 ($p > 0.05$), indicating no significant difference, indicating that the buoyancy forces acting on the seeds remained constant regardless of moisture content.

The Reynolds number also did not show a significant change ($F = 1.45$, $p > 0.05$), meaning that the airflow characteristics around the seeds were not significantly affected by moisture depending on the speed and seed size. The surface area (mm²) had an F-value of 1.67 ($p > 0.05$), confirming that the surface area of the seeds remained constant across moisture levels, probably because physical expansion due to water absorption was minimal. The mass (mg) exhibited a highly significant difference ($F = 302.45$, $p < 0.05$), reflecting a strong effect of moisture on seed weight, consistent with water absorption increasing mass. The density (kg m^{-3}) also showed a similarly significant change ($F = 298.67$, $p < 0.05$), indicating that moisture increased the density of the seed, possibly filling the internal structures with water. Finally, the F value of the

shape factor was 0.34 ($p > 0.05$), indicating that there was no significant difference in seed shape between moisture levels, as shape is determined primarily by genetic factors rather than moisture. The results of this ANOVA test indicate that moisture significantly affected drag, terminal velocity, mass, and density, while lift coefficient, reynolds number, surface area, and shape were relatively unaffected, indicating that certain aerodynamic and physical properties were affected by moisture content.

Table 3 presents the groupings obtained from Duncan's multiple comparison test in detail; the different letters used in this table (A, B, C, D) clearly show that there are statistically significant differences between the moisture content levels examined. These groupings visually and quantitatively express the extent to which the variables measured at specific humidity levels differ from each other.

Table 3

Duncan test for aerodynamic properties of pepper seeds with different moisture contents

Parameters	5.4%	8.6%,	12.1%	15.4%
Drag Coefficient	A	B	C	D
Terminal Velocity (m	D	C	B	A
Lift Coefficient	A	A	A	A
Reynolds Number	A	A	A	A
Surface Area (mm²)	A	A	A	A
Mass (mg)	D	C	B	A
Bulk Density (kg m^{-3})	D	C	B	A
Shape Factor	A	A	A	A

The parameters with ANOVA test results ($p < 0.05$: drag coefficient, terminal velocity, mass, density) were determined to have significantly different moisture levels by applying Duncan's multiple range test, while the parameters that were not significant were assigned to the same group (A) due to no difference.

The average values for drag coefficient were found to be 0.475, 0.445, 0.415 and 0.387 at 5.4%, 8.6%, 12.1% and 15.4% moisture levels, respectively. Duncan's test grouped them as A, B, C and D, respectively, and showed that each moisture level formed a separate group, with the friction coefficient decreasing as moisture increased.

This suggests that wetter seeds may have smoother surfaces and reduce air resistance. The mean values of terminal velocity (m/s) were measured as 2.50, 2.63, 2.74 and 2.83 at 5.4%, 8.6%, 12.1% and 15.4% moisture levels respectively and were grouped as A, B, C and D respectively.

This confirms that terminal velocity increased with higher moisture content which is due to the relative decrease in drag force with decreasing surface roughness despite the increase in seed mass and density. The mass and density of seeds also increased with moisture content. Both parameters were grouped as A, B, C and D according to increasing moisture content.

These results showed a clear trend that mass increased with moisture due to water absorption while density also increased significantly with moisture and the internal structure of the seed was filled with water.

As a result of the test, lift coefficient, Reynolds number, surface area and shape factor were all placed in Group A for the parameters that were not significant, indicating that there was no significant difference between them and that these properties remained consistent across humidity levels. Duncan test results emphasize that humidity significantly changes mass and density, each humidity level forms different groups, while drag and terminal velocity decrease with increasing humidity, reflecting aerodynamic changes.

The ANOVA test results show that moisture content significantly affects the drag coefficient, terminal velocity (m s^{-1}), mass (mg) and density (kg m^{-3}) values with high f statistics and p values less than 0.05, while lift coefficient (Cl), Reynolds number, surface area (mm²) and shape factor show no significant difference ($p > 0.05$).

The Duncan test results showed that different moisture levels produced statistically significant differences in the aerodynamic and physical properties. The increase in moisture content caused significant increases in seed mass and bulk density, while it caused a decrease in drag coefficient and an increase in terminal velocity.

These changes are thought to be related to the fact that moisture changes the porosity structure of the seed, surface roughness and hence liquid-particle interactions. These findings indicate that moisture levels play an important role in seed aerodynamic and physical properties and have important consequences for seed transportation and processing.

CONCLUSIONS

This study presents a comprehensive analysis of the aerodynamic behavior of pepper seeds under changing moisture conditions, providing critical insights into how water content regulates key physical and functional properties. The findings show that increasing seed moisture content leads to significant increases in bulk and bulk density, accompanied by a decrease in friction coefficient and an increase in terminal velocity. In contrast, parameters such as lift, estimated surface area, shape factor, and airflow pattern were not significantly affected by moisture change.

These results highlight the complex yet systematic effect of moisture on seed structure and performance. Water absorption appears to alter internal and surface properties such as porosity and roughness, which in turn alter seed-air interactions. This nuanced relationship suggests that moisture is not merely a passive factor but a determinant of seed mechanics, particularly in contexts involving pneumatic conveying, mechanical sorting, and air-assisted planting systems.

From an applied perspective, the implications are significant. Higher moisture content may necessitate recalibration of pneumatic systems to reduce clogging and ensure consistent seed flow. Additionally, the observed increase in terminal velocity may affect seed dispersal dynamics, particularly in wind-dispersed species, potentially affecting ecological dispersal and establishment rates.

Given the increasing variability in climate conditions and the prevalence of moisture fluctuations in many agricultural regions, these findings advocate for moisture-adaptive seed processing and storage protocols. Incorporating moisture-responsive parameters into the design of agricultural machinery and processing systems may increase operational efficiency, reduce seed loss, and improve crop establishment under a variety of environmental conditions.

In conclusion, this study highlights the importance of integrating seed moisture dynamics into both experimental design and technological applications in seed science. Recognizing seeds as moisture-responsive systems rather than static materials opens new avenues for innovation in precision agriculture, postharvest processing, and climate-resilient farming practices.

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CONSIDERATIONS REGARDING THE USE OF MODERN EQUIPMENT FOR THE EFFICIENT UTILISATION OF PERMANENT PASTURES

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CONSIDERAȚII PRIVIND UTILIZAREA ECHIPAMENTELOR MODERNE PENTRU VALORIFICAREA EFICIENTĂ A PĂȘUNILOR PERMANENTE

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ABSTRACT

Permanent pastures represent an essential resource for animal feed and therefore contribute directly to the sustainability of livestock farms. Proper maintenance of these resources requires the use of modern equipment adapted to the pedo-climatic conditions and to the vegetation type. Pastures provide a range of ecosystem services, including regulation and storage of water flows, nutrient cycling and carbon sequestration. Grazing is the most important factor shaping and stabilising pasture biodiversity. Opportunities for exploiting pastures lie in the nutritional and health-promoting qualities of milk and dairy products, particularly milk from cows fed on pasture. The beneficial effects of grazing on animal health and welfare are not negligible. Available organisational innovations can help improve the management of livestock grazing and, above all, lead to a better understanding of the impact of grazing on the environment and climate change. This paper presents modern equipment used in pasture management operations as well as its impact on productivity and biodiversity conservation.

REZUMAT

Pășunile permanente reprezintă o resursă esențială pentru hrana animalelor, contribuind la sustenabilitatea fermelor zootehnice. Întreținerea corespunzătoare a acestora presupune utilizarea unor echipamente moderne adaptate condițiilor pedoclimatice și tipului de vegetație. Pășunile oferă servicii ecosistemice, inclusiv reglarea și stocarea fluxurilor de apă, ciclul nutrienților și sechestrarea carbonului. Pășunatul este cel mai important factor care modelează și stabilizează biodiversitatea pășunilor. Câteva oportunități pentru hrănirea pășunilor sunt calitățile nutritive și benefice pentru sănătate ale laptelui și produselor lactate, în special ale laptelui provenit de la vacile hrănite pe pășuni. Efectele benefice ale hrănirii pe pășuni asupra sănătății și bunăstării animalelor nu sunt nesemnificative. Inovațiile organizaționale disponibile pot ajuta la o mai bună gestionare a pășunatului animalelor și, mai presus de toate, la o mai bună înțelegere a impactului procesului de pășunat asupra mediului și a schimbărilor climatice. Lucrarea prezintă echipamente moderne utilizate în lucrările de administrare a pășunilor, precum și impactul acestora asupra productivității și conservării biodiversității.

INTRODUCTION

Permanent grasslands, including pastures, are characterised by a diverse species composition resulting from interspecific competition modified by human activity. The most important factors are the habitat conditions and the method and intensity of agricultural use, which determine the type of sward and its natural values. One of the characteristics of grasslands of high natural value is their richness in species. However, maintaining this richness is not a priority on farms focused on intensive animal production. In such farms the main goal is to obtain large quantities of valuable forage, so the sward composition is generally poor in species, dominated by selected grasses with a proportion of legumes and only a few herb species. Many of these herbs are considered weeds from a production standpoint and indicate degradation. By contrast, high species diversity is favoured by extensive grazing and limited use of sward management practices (*Wróbel et al., 2023*).

One of the most important factors shaping and stabilising valuable communities in permanent grasslands is sustainable grazing, which is sometimes used as a protective treatment to arrest secondary

succession. Grazing has a beneficial effect on floristic composition and sward structure, contributing to the maintenance of an open pastoral landscape and the conservation of species-rich habitats. The vegetation structure of pastures is the result of processes and environmental factors determined by the grazing animals—namely their dietary requirements and preferences and the intensity of grazing.

Moderate trampling by grazing animals leads to localised damage and the formation of bare patches where seeds can germinate; it also allows light to reach the lower parts of the sward, promoting the development of light-loving species. Furthermore, animals transport plant diaspores, facilitating their reproduction and spread, and their excreta supply nutrients locally, creating numerous micro-habitats (*Wróbel et al., 2023, Musagaliev & Shodiev, 2023*).

Grazing has been practised since the beginnings of agriculture. According to the Food and Agriculture Organization, around 60 % of the world's grasslands (slightly less than half of the Earth's land area) are occupied by grazing systems. Such systems provide about 9 % of global beef production and roughly 30 % of the world's sheep and goat meat.

For about one hundred million people in arid areas, and probably a similar number elsewhere, livestock grazing is the only possible livelihood. Pasture-based dairy systems are found mainly in temperate regions, where grass is the cheapest feed used in milk production (*De Haan et al., 1997*). Grazing can also be used in dairy-cow feeding systems elsewhere in Europe, but its importance is lower.

It is estimated that 98 % of dairy farms in Ireland and 92 % of those in Britain operate pasture-based systems, compared with only 20 % in the Czech Republic, less than 10 % in Greece and virtually none in Bulgaria. Even herds with access to pasture are usually housed during winter and the calving period (*Wilkinson et al., 2020; Van den Pol-van Dasselaar et al., 2020; Crump et al., 2019*).

In general, pasture grass is a higher-quality feed for milk production than grass silage (*Kennedy et al., 2005; Hurtado-Uria et al., 2013; Ruelle et al., 2018*). In the temperate regions of Europe, grass growth is highly variable—differing from year to year, between seasons and between regions. It depends on many factors: pasture management, sward renewal practices, the level of fertilisation, the evolution of weather conditions (e.g., precipitation, temperature, solar radiation) and soil type. The nutritional value of the sward also varies with season, growth stage and regrowth age.

The quality of pasture grass can be optimised through rational grazing and pasture management. For example, rotation length, pre-grazing biomass and sward height before and after grazing can affect grass quality and availability. A leaf-rich sward in spring has a high nutritional value, whereas a sward in the reproductive stage in summer contains more fibre and is less digestible. The nutritional value of the sward also depends on its botanical composition; swards with a significant proportion of legumes often have a higher nutritional value than swards composed only of grasses (*Wims et al., 2010; Ganche et al., 2013; McDonald et al., 1998; Egan et al., 2018*).

Properly managed pastures provide grazing animals with high-quality forages containing energy, protein, macro- and micro-elements and vitamins. Alongside valuable grasses and legumes, the sward contains dicotyledonous forbs.

These forbs contain biologically active substances—tannins, flavonoids, saponins, pectins, terpenes, alkaloids, phenols and essential oils—that have positive effects on the digestive system and the health of cattle (antioxidant and antiparasitic effects, improved immunity) and improve the quality of beef and dairy products (*Riberio Filho et al., 2003; Peyraud & Delagarde, 2013; MacAdam & Villalba, 2015; Distel et al., 2020; Niderkorn & Jayanegara, 2021; Kaur et al., 2021*).

Despite the importance of grazing, current trends in European livestock husbandry are reducing the popularity of pasture-based feeding for dairy cows. The reasons vary, owing mainly to the different farming systems typical of each region. In Central Europe, dairy farmers are under pressure to maximise milk output. Consequently, dairy cows are often not grazed but are kept indoors throughout their lives and fed mainly on silage and concentrates (*Wilkinson et al., 2020; Van den Pol-van Dasselaar et al., 2020; Läpple & Sirr, 2019*).

Grazing requires more time and labour than keeping cattle indoors or in loose housing. It also involves costs for purchasing and installing fences and for delimiting paddocks. Electric fences and wire mesh structures may also disrupt the natural landscape and prevent the migration of wild species (*Langworthy et al., 2021*).

Agriculture is significantly influenced by climate change and is at the same time a driver of climate change through the release of greenhouse gases into the atmosphere. Reducing agriculture's carbon

footprint is therefore essential to mitigate climate change. Agriculture and forestry can also remove CO_2 from the *atmosphere. Grasslands play a significant role in climate change because of their large carbon stocks and fluxes (Bai & Cotrufo, 2022; Rasche et al., 2023*).

Demand for animal-based protein products is predicted to increase by more than 70 % in the coming decades, as wealth increases in developing countries. Consequently, this could lead to an 80 % increase in greenhouse-gas emissions from agriculture if not mitigated. Pasture-based agriculture has an important role in increasing food production in an environmentally sustainable manner.

Over recent decades there has been a 30 % reduction in European grassland use owing to increased production efficiency and the controllability of feed in confinement systems, where animals are fed indoors. In contrast, pasture-based systems in suitable climates have the potential to be more economically and environmentally sustainable than confinement systems (*Van den Pol-van Dasselaar et al., 2020; Hennessy et al., 2015; Barthram et al., 2005; Klootwijk et al., 2019; Nakagami, 2016*).

Nevertheless, they are hindered by reduced feed controllability due to the spatial and temporal heterogeneity of pastures: the amount of available herbage can vary between 15 % and 60 % owing to selective grazing, dung patches and seasonal changes in sward morphology, making accurate measurement and allocation for grazing difficult (*Herrero et al., 2015; Henchion et al., 2017; Tilman & Clark, 2014; Huyghe et al., 2014; Hennessy et al., 2020).*

To maintain the productive capacity of these ecosystems, proper management is required, involving both agronomic measures and specialised agricultural equipment. Inadequate maintenance leads to pasture degradation, reduced biodiversity and the emergence of invasive species.

This paper presents an overview of modern equipment used in permanent pasture management and discusses how such technologies can enhance productivity while preserving biodiversity.

MATERIALS AND METHODS

Precision technology enables efficient pasture management. Using GPS, drones and vegetation sensors makes it possible to monitor pasture condition, apply fertilisers variably and intervene rapidly in problem areas. Such approaches reduce costs and improve sustainability.

Developing accurate grass-measurement technologies is vitally important for ensuring the future sustainability of pasture-based animal production systems. There is potential to increase grassland production sustainably by measuring herbage quantity and quality more precisely. One of the main obstacles—sward heterogeneity—is discussed together with optimal sampling techniques to address it.

With respect to grass quality, there are no established farm-level methods that farmers can use to estimate the quality of grass on their own pastures.

Existing methods for qualitative analysis are usually laboratory-based and involve time-consuming pre-processing such as grinding and oven drying, which may take several days. Important quality parameters for grazing systems include dry matter, digestible dry matter, metabolizable energy, digestible organic matter, crude protein and water-soluble carbohydrates.

Precision agriculture technologies offer significant potential to improve the availability and accuracy of grassland-measurement information. Precision agriculture focuses on acquiring precise field data at spatial and temporal scales that capture variability and allow targeted management responses, aiming to increase economic returns and reduce environmental impact.

Adoption of precision technologies has been relatively slow in grassland farming compared with arable farming, partly because pastures are more diverse in terms of spatial variation in soil and sward characteristics and because grass species change rapidly over time.

In the present context, ground-based sensing refers to non-spectral sensors that interact with the sward at or near ground level. Mobile ground-based sensing using electrodes was employed by Vogel and colleagues to investigate relationships between soil pH, moisture content and spatial variation in herbage mass on grazed German pastures.

Their study used a tractor-mounted Veris mobile sensor platform (Fig. 1) for rapid soil analysis; apparent soil electrical conductivity was measured to predict soil moisture.

Fig. 1 - Mobile Veris sensor platform mounted on a tractor for on-the-go soil analysis on pastures
(*Vogel, et al., 2019*)

The use of a sensor to measure sward height directly by means of ultrasound was investigated on mixed-species German swards by Reddersen et al., 2014. They found that it predicted herbage mass with reasonable accuracy (R^2 = 0.73–0.76, RMSECV = 0.88–1.17 t DM ha^{-1}). Moreover, combining ultrasonic sward-height data with remote-sensing data in a multi-sensor approach (leaf area index and hyperspectral sensors) increased prediction accuracy by 30 %. An earlier study by Fricke et al. investigated combining ultrasonic height sensing with GPS on a vehicle for real-time, on-the-go measurement and rapid mapping of pasture yield, as illustrated in Figure 2a.

That study highlighted several limitations of ultrasonic measurement, including poor accuracy caused by the wide ultrasonic response area and low responsiveness to changes in sward geometry and heterogeneity. Nevertheless, it emphasised the potential of combining networks of low-cost ultrasonic sensors, which could be mounted on tractors or mowers, to generate inexpensive herbage-mass predictions with minimal effort. Safari et al. compared mobile ultrasonic sensing and spectral detection (Figure 2b) with static detection, reporting lower prediction accuracy for mobile measurements owing to positional errors caused by soil-profile variation. Moeckel et al. obtained poor results (R^2 = 0.36–0.74, SE = 675–1,118 kg DM ha^{-1}) when predicting herbage mass using ultrasound on mixed-species pastures and reported large errors on mature swards owing to patches of rejected grass remaining after grazing.

Their study further explored the potential of combining spectral data from spectrometers and satellites with ultrasound and found that using both visible and near-infrared spectral data improved herbage-mass prediction (R^2 = 0.66–0.88, SE = 485–866 kg DM ha^{-1}). A similar ultrasound system, which could be mounted on an agricultural vehicle travelling at 20 km h^{-1}, achieved prediction accuracies of R^2 = 0.75 and SE = 270–350 kg ha^{-1} on New Zealand pastures. Ultrasonic sensing is relatively fast, inexpensive and easy to implement, with potential for mobile applications; conversely, it has accuracy limitations arising from the large variation in signal responses to sward heterogeneity.

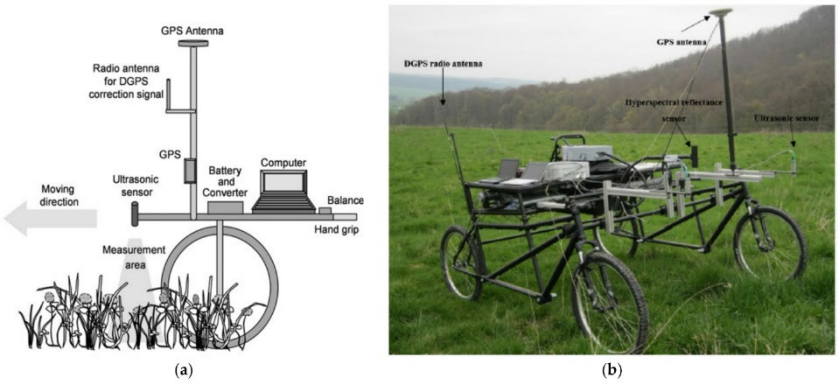

Fig. 2 (a) - Diagram of the on-the-go grass-measurement system presented in *(Fricke et al.)*
(b) Image of a similar system
(Safari et al., 2016)

Ground-based sensing can enable grass measurement by autonomous ground vehicles (AGVs) working remotely at close proximity to the soil surface. Research on AGVs for precision agriculture applications has focused mainly on arable farming. A more recent adaptation of the C-DAX platform is a

proposed pasture robot currently under development in New Zealand (*Manderson & Hunt, 2013; Safari et al., 2016; Murphy et al., 2021*).

The concept combines an AGV with the C-DAX system: the robot is designed to navigate autonomously from a central charging station to a paddock and to traverse the pasture according to a pre-programmed sampling strategy, eliminating manual labour. An entire 2 ha paddock could be sampled for mapping in five hours, or a representative area could be sampled for basic pasture management in less than thirty minutes.

The potential to mount soil-sampling and herbage-quality sensors on this system is also being considered. Gobor et al. proposed a similar robotic system for use on German pastures. Their concept incorporates a mulching unit on the robotic platform (Fig. 3) so that rejected pasture areas identified by a sward-height sensor can be mulched to encourage regeneration of high-quality swards; areas with low herbage mass could be reseeded using a seeder mounted on the robot. Sampling-protocol design is a significant consideration when using AGVs for pasture measurement.

Designing optimal AGV sampling protocols should adhere to best practices for pasture sampling, yet labour and measurement time do not impose the same constraints when using AGVs. Compared with unmanned-aerial-vehicle (UAV) remote sensing, AGV systems have disadvantages—slower data collection, sward damage caused by vehicle tracks and higher cost—but these may be offset by higher resolution and reduced climatic noise (*Safari et al., 2016; Moeckel et al., 2017*).

Fig. 3 - Concept of the robotic pasture system proposed by *Gobor et al. 2015*, incorporating a mulcher and a seeder

Remote sensing refers to detection techniques operating more than two metres above ground level. This category includes methodologies using drones, manned aircraft and satellites. In the past decade, research on remote sensing methods for predicting grass yield and quality has increased. Remote sensing can cover large sampling areas with minimal labour.

Various remote-sensing technologies can be mounted on drones flying at low altitude to obtain high-resolution spectral data. Rueda-Ayala et al. found poor correlations ($R^2 < 0.6$) between RGB wavelength data and herbage mass on Norwegian PRG-dominated pastures, and reported difficulties in measurement accuracy due to environmental factors such as wind speed, sunlight and cloud cover. However, they observed that UAV-based detection was less variable than ground-based data.

Askari et al. showed that red and green wavelength bands were important for predicting crude protein content through UAV detection on Irish PRG pastures. Capolupo et al. demonstrated that hyperspectral drones could predict sward height ($R^2 = 0.70–0.86$, RMSE = 2.13–2.29 cm), herbage mass ($R^2 = 0.36–0.83$, RMSE = 2.95–3.81 kg DM per plot) and crude protein ($R^2 = 0.56–0.76$, RMSE = 11.73–12.28 g kg^{-1} DM) on plots in controlled German studies.

Multispectral sensors (MS) emit light in discrete spectral bands and at broader resolutions than hyperspectral sensors and have been used more frequently in UAV research for pasture analysis. A major advantage of MS devices is that they are usually cheaper than hyperspectral instruments.

Pullanagari et al. reported reasonable accuracy ($R^2 = 0.60–0.68$; RMSE = 0.65–5.27 %) for crude protein, metabolizable energy and organic matter digestibility on PRG-dominated pastures in New Zealand over two grazing seasons, using a proximal MS sensor covering 16 discrete wavelengths (460–1680 nm).

An important drawback identified was that many MS sensors depend on natural light to illuminate the sward, so low light intensity can cause sampling problems. Askari et al. obtained good prediction results for herbage mass (R^2 = 0.78, RMSE = 215 kg DM ha^{-1}) and crude protein (R^2 = 0.77, RMSE = 13.6 g kg DM^{-1}) using UAV-borne MS sensing (Fig. 4) on Irish PRG pastures across two grazing seasons.

Togeiro de Alckmin et al. reported that MS sensing (R^2 = 0.79, RMSE = 405.8 kg DM ha^{-1}) had a smaller error (by 116 kg DM ha^{-1}) than rising-plate meters for predicting herbage mass when an optimal selection of vegetation indices was used. Oliveira et al. showed that combining hyperspectral detection with 3-D imaging outperformed MS measurements on Finnish swards, accurately predicting herbage mass (relative prediction error of 14.6 %), digestibility (1.9 %) and nitrogen content (13.6 %).

(a) (b)

Fig. 4 - (a) UAV equipped with a multispectral sensor; (b) example of a UAV survey from *Askari et al., 2019*

RESULTS

Recent developments in robotics and artificial intelligence are transforming agricultural practices. Results from the literature show that advanced technologies such as automation, service robots and AI-assisted systems address labour shortages, improve efficiency and enhance product quality.

Agriculture is indispensable to humanity: people rely on it to produce food, so there must be continuous supply and production to meet the needs of a growing population. Owing to the shortage and ageing of the rural workforce in recent years, agricultural production must depend on mechanisation to improve efficiency.

To enhance labour productivity and reduce costs, however, automation and technologisation represent the inevitable path of agricultural development beyond mechanisation (*Belanche et al., 2020; Wirtz et al., 2018; Genesys, 2019*).

The world is moving towards the fourth industrial revolution, and technologies such as the Internet of Things, artificial intelligence and cloud computing are becoming mainstream. Image processing plays a very important role in industrial production: it can visualise the anatomical structure of products, check and evaluate their advantages and disadvantages in real time and reduce unnecessary losses. Consequently, operators need to avoid the errors inherent in traditional manual judgement and to accelerate the harvesting of agricultural products.

Through deep learning and advances in image-recognition technology, high-tech innovative agriculture can be developed from traditional agriculture to solve problems such as labour shortages and limited research and development, thereby improving productivity and the international competitiveness of agricultural products.

Advanced robotics, artificial intelligence and machine-learning technologies enable providers to offer their services with increased productivity, effectiveness and efficiency. Service robots and artificial intelligence promise to increase productivity and reduce costs, leading to substantial growth in service-robot sales. Developed countries are currently affected by an ageing population and declining birth rates, causing a continuous decline in the workforce and a serious lack of labour productivity. How to bridge this labour-demand gap is a challenge many countries are eager to solve.

The rise of robotics has been felt across all industries. High-tech robots, coupled with artificial intelligence and machine learning, can deliver greater productivity and better product quality and steadily increase service efficiency, thereby improving customer satisfaction. A survey of business leaders in the United States showed that 24 % of companies were already using artificial intelligence and 60 % expected to use it by 2022. Sales of service robots continue to grow by more than 30 % per year, and the International

Federation of Robotics predicts that over the next decade the range of professional and personal uses for service robots will expand further and permeate various industries to support production and service activities.

Artificial intelligence specifically refers to machines that exhibit aspects of human intelligence. Initially conceived as a way to combine perception, reasoning and learning, AI development has focused increasingly on algorithms, while robotics has addressed mechanical operation. From a service-management perspective, the value of AI derives not from its virtual or unseen use but from its ability to interact socially with customers.

With the rapid development of AI, intelligent robots have been widely adopted in fields such as agricultural management and water-resource management. In the past, machine operators were separated from machinery for safety reasons, but Industry 4.0 aims to support future factories and reduce operator fatigue: robots are integrated into assembly lines to work with humans, producing high-quality goods and completing tasks more efficiently and satisfactorily.

Fig. 5 - Finished product of the automatic robotic lawn mower
(*Liao et al., 2021*)

Companies such as Honda and Husqvarna have recently launched a range of robotic lawn mowers priced between USD 1,000 and USD 2,500. At present, such mowers are more popular in Europe; sales in the United States are not as strong. Some mowers from the Swedish company Husqvarna cost USD 5,100 per unit and can handle steep slopes (45°) and adverse weather. With GPS-assisted navigation and Automower Connect, the mowers can be controlled from anywhere.

Robotic mowers from iRobot can memorise positions and automatically generate a digital map of the area to be mown; they can also be programmed to mow regularly and to control the cutting height. Users of the Honda mowers can mow without pushing and benefit from anti-theft alerts; these units cost USD 2,500. Robotic lawn mowers are diverse and offer different functions, allowing consumers to select a model to suit their needs

CONCLUSIONS

Efficient management of permanent pastures is impossible without modern equipment adapted to specific needs. Correct application of agricultural technologies leads to increased productivity and ecosystem conservation. In the context of climate change and environmental-protection requirements, smart mechanisation and precision agriculture will become central to the sustainable exploitation of pastures.

Recent advances in robotics and artificial intelligence provide promising solutions for labour shortages in agriculture and enhance precision in pasture management, paving the way for technologically driven pastoral systems. Integrating autonomous ground vehicles, remote sensing and AI-driven decision support will enable farmers to monitor forage quantity and quality more accurately, leading to sustainable and resilient livestock production.

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BLACK SOLDIER FLY LARVAE (*HERMETIA ILLUCENS*): FROM SUSTAINABLE ANIMAL FEED TO EMERGING HUMAN FOOD SOURCE

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LARVELE DE MUSCĂ SOLDAT NEGRU (HERMETIA ILLUCENS): DE LA FURAJ SUSTENABIL PENTRU ANIMALE LA SURSĂ ALIMENTARĂ EMERGENTĂ PENTRU OAMENI

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ABSTRACT

The black soldier fly (BSF, Hermetia illucens) has emerged as a promising agent for circular bioeconomy models, addressing critical challenges related to organic waste management and protein supply. This paper explores the biological, nutritional, and functional attributes of BSF larvae that support their use in feed and food systems. The larvae demonstrate exceptional bioconversion efficiency, transforming a wide range of organic residues into high-value biomass rich in proteins, lipids, and micronutrients. Particular attention is given to their application in aquaculture, poultry, swine, and pet nutrition, where they enhance growth, immunity, and sustainability. BSF-derived products also show potential as alternative protein sources for human consumption, offering high nutritional value and low environmental impact. However, safety concerns, regulatory hurdles, and cultural perceptions continue to limit widespread adoption. The paper also reviews recent scientific findings, industrial applications, and legal frameworks governing BSF larvae use in the EU and globally. Overall, BSF larvae represents a sustainable and multifunctional protein source with expanding applications in both feed and food industries, provided that safety, processing standards, and consumer acceptance are adequately addressed.

REZUMAT

Musca soldat negru (BSF, Hermetia illucens) este tot mai recunoscută ca soluție sustenabilă în bioeconomia circulară, contribuind atât la valorificarea deșeurilor organice, cât și la diversificarea surselor de proteine. Lucrarea analizează caracteristicile biologice și nutriționale ale larvelor de BSF, care permit utilizarea acestora în sistemele de furajare și alimentație. Larvele prezintă o eficiență ridicată de conversie, transformând diverse resturi organice în biomasă bogată în proteine, lipide și micronutrienți. Aplicațiile lor în acvacultură, avicultură, creșterea porcinelor și hrana animalelor de companie sunt bine documentate, evidențiind beneficii privind creșterea, imunitatea și sustenabilitatea. Produsele derivate din BSF sunt tot mai explorate ca surse proteice pentru consumul uman, având valoare nutrițională ridicată și impact ecologic redus. Totuși, adoptarea largă este limitată de provocări legate de siguranță, reglementări stricte și bariere culturale. Lucrarea sintetizează și rezultatele recente, aplicațiile industriale și cadrul legislativ aplicabil la nivel european și global. În ansamblu, larvele de BSF reprezintă o sursă sustenabilă și multifuncțională de proteine, cu utilizări în creștere, atât în industria furajelor, cât și în alimentație, cu condiția respectării standardelor de siguranță și a acceptabilității consumatorilor.

INTRODUCTION

The growing global demand for sustainable food systems and alternative protein sources is intensifying due to the convergence of multiple crises: rapid population growth, climate change, depletion of agricultural resources, and unsustainable waste generation.

According to the United Nations, the world population is projected to exceed 9.7 billion by 2050, placing unprecedented pressure on land, water, and energy resources. This situation underscores the urgent

need for innovative food production strategies that are both ecologically sound and economically viable. Conventional meat production is no longer considered a sustainable source of protein (*Miron et al., 2023a*).

At the same time, the volume of organic waste, including food scraps, agricultural by-products, and animal manure, continues to grow, leading to significant greenhouse gas (GHG) emissions and environmental degradation when inadequately managed.

In this context, the black soldier fly (BSF, *Hermetia illucens*) has emerged as a promising solution within circular bioeconomy models. Its larvae can convert a wide variety of organic residues into high-value biomass, including protein-rich material suitable for use as animal feed and, increasingly, as a potential human food source. The valorization of BSF larvae addresses two critical challenges: improving organic waste management and diversifying protein supply chains in a sustainable manner.

Globally, insects are increasingly recognized as high-efficiency bio-converters and sustainable protein sources due to their low environmental footprint and ability to thrive on organic waste streams. Compared to conventional livestock, insect farming requires significantly less water, land, and feed, while producing far lower GHG emissions (*Seyedalmoosavi et al., 2022*).

Consequently, insects are being explored as viable alternatives for both feed and food applications in circular and resilient food systems. Insect farming has been proposed as a sustainable protein production strategy in response to multiple challenges: limited natural resources, climate change, supply chain disruptions, and competition between food, feed, and biofuel production (*Muscat et al., 2020*).

The production of edible insects as a protein source is considered two to five times more environmentally efficient compared to conventional animal-based protein sources (*Cruz et al., 2023*).

Table 1 presents a comparative assessment of energy use and environmental impacts associated with alternative protein sources.

Table 1

Energy and environmental impacts of the alternative protein sources

(EPRS, 2024)

Type of protein	Source	Comparison with conventional protein sources			
		Energy	**Land use**	**Water use**	**GHG emissions**
Insects	Black soldier fly	Higher to much higher than soy protein, depending on animal diet	Similar to feed formulations	Significantly higher than feed formulations	Similar to feed formulations
	Mealworm	Slightly higher than dairy and chicken; lower than beef	Significantly lower than beef; similar to chicken and feed formulations	Higher than beef and significantly higher than chicken and feed formulations	Significantly lower than beef; slightly lower than poultry; similar to feed formulations
Algae	Sugar kelp (*Saccharina latissima*)	Higher to much higher than soy protein	Lower to significantly lower than all conventional proteins	Much lower than conventional proteins	Higher than soy protein; lower than dairy and chicken; significantly lower than beef
	Spirulina or *Chlorella*	Lower to higher than beef, depending on the production process	Lower to significantly lower than all conventional proteins	Much lower than all conventional proteins	Significantly higher than soybean; higher than dairy and chicken; significantly lower than beef
Microbial fermentation	Mycoprotein (*Fusarium venetatum*)	Lower, similar to or higher than meat and soy protein	Lower than chicken; significantly lower than beef	Significantly lower to higher than meat	Lower than chicken; significantly lower than beef
	Dairy alternative	Lower, similar to or higher than dairy	Significantly lower than dairy	Lower, similar to or higher than dairy	Lower to significantly lower than dairy

Cultured meat	Cultured chicken	Higher to much higher than conventional chicken	Similar to or lower than chicken	Higher or similar to chicken depending on method	Higher than chicken
	Cultured beef	Slightly lower to much higher (up to 3 times higher) than beef	Significantly lower than beef	Significantly lower than beef	Lower to much lower than beef

To produce 1 kg of BSF larvae, only 1.5 kg of feed is required, an efficiency far superior to that of other livestock. For comparison, poultry requires 2.5 kg of feed, pigs 5 kg, and cattle up to 10 kg to achieve the same weight gain (*FAO, 2013*). This demonstrates the exceptional feed conversion efficiency of BSF larvae.

Figure 1 compares the amounts of water, land, and feed required to produce 100 kg of protein from various sources, emphasizing the resource efficiency of insect farming over conventional protein production.

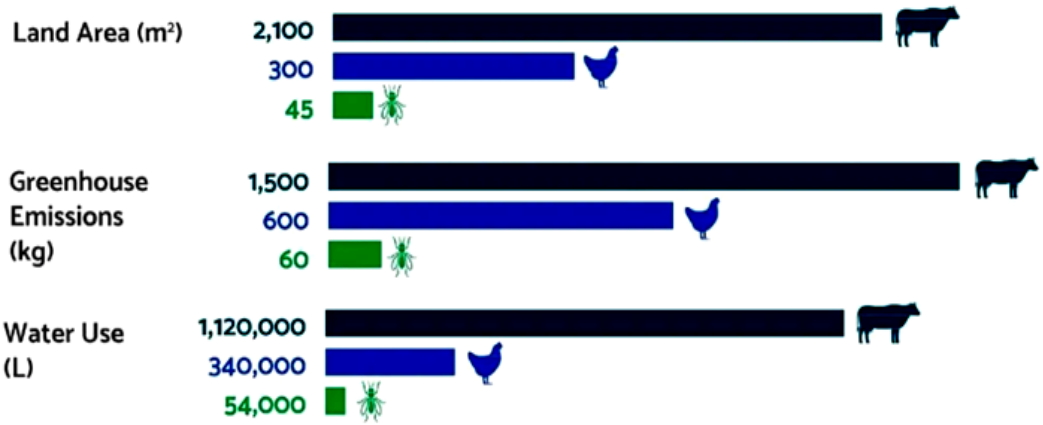

Fig. 1 - Resource inputs for insect protein production: a comparative analysis with beef and poultry (*https://hexafly.com/*)

To date, large-scale applications of BSF larvae have primarily focused on animal nutrition, particularly in aquaculture, poultry, and pet food sectors. However, advances in insect processing technologies, coupled with growing consumer interest in sustainable and functional foods, have created new opportunities for incorporating BSF-derived products into human diets (*Gahukar, 2011*). This potential is especially relevant in regions with limited agricultural resources or high levels of food insecurity, where insect-based proteins offer a scalable, nutrient-dense solution for enhancing food system resilience.

While the biological efficiency of BSF larvae in organic waste conversion is well documented, the next critical step is to understand how the resulting biomass can be safely and effectively integrated into feed and food chains. However, the adoption of insect-derived products is still limited by regulatory uncertainty and cultural resistance in many parts of the world.

A clear understanding of safety, consumer acceptability, and legal frameworks is essential to facilitate the global integration of insect-based proteins.

This review explores the dual role of BSF larvae as both animal feed and an emerging human food source. The analysis will examine the nutritional composition and safety aspects of BSF-derived products, current industrial applications, regulatory and cultural considerations, and the broader implications for food security and sustainable development.

By synthesizing existing scientific evidence and the regulatory landscape, this paper aims to support the integration of BSF-based proteins into future food systems.

BLACK SOLDIER FLY: BIOCONVERSION AND BIOLOGICAL PROFILE

Hermetia illucens is a dipteran insect of tropical origin, currently recognized as one of the most efficient bioconversion agents for organic waste streams. Its development includes five stages: egg, larva, prepupa, pupa and adult.

BSF larvae demonstrates resilience to challenging environmental conditions, including periods of drought, limited oxygen availability, and temporary food scarcity. However, optimal conditions for adult BSF mating and oviposition occur within a temperature range of 27–37 °C, with ambient humidity levels of 40–60% and relative humidity between 60–70% (*Jalil et al., 2021*).

Under controlled rearing conditions, the complete life cycle can be completed within 35–45 days, with the larval stage lasting around two weeks and representing the most metabolically active phase (*Chia, 2019*). During this phase, the larvae exhibit voracious feeding behavior and can degrade a wide range of organic substrates, including agricultural by-products, household food waste, and animal manure.

This results not only in a substantial reduction in waste volume and environmental pollutants, but also in the accumulation of valuable larval biomass. Both acidic (pH 2, 4, and 6) and alkaline (pH 8 and 10) environments support relatively high survival rates of BSF larvae. However, the pH range of 6 to 10 has been identified as significantly more favorable for optimal larval development and increased biomass accumulation compared to the more acidic range of pH 2 to 4 (*Meneguz et al., 2018; Pang et al., 2020*).

This enhanced performance is attributed to the alkalization of the substrate induced by larval metabolic activity, which promotes protease enzyme activation. The resulting increase in proteolytic activity facilitates greater protein availability, thereby supporting improved larval growth and weight gain.

At the final stage of development, larvae can reach lengths of up to 27 mm, widths approaching 6 mm, and a weight near 220 mg (*Makkar et al., 2014*). During the prepupal phase, the last stage before metamorphosis, they clear their digestive tracts and depart from their feeding environment to find a dry, protected site suitable for pupation.

This instinctive behavior, termed “self-harvesting,” has greatly simplified larval collection by removing the need for manual harvesting efforts previously required in farming operations. At this point, the larvae have attained their largest physical dimensions and possess a protein content between 35–45%, and approximately 35% lipids. They usually complete their transformation into adults within about two weeks. The lipids reserved in their body is converted into energy for adults’ mating and continuous life cycle (*Amrul et al., 2022*).

Compared to other insects used for organic waste management, BSF larvae offer multiple advantages: a rapid growth cycle, high feed conversion rate (<2), resilience to many pathogens, and adaptability to large-scale production systems.

Moreover, BSF do not act as vectors for human diseases and do not require feeding during the adult stage, which simplifies management in industrial environments. Their ability to thrive on low-value substrates, combined with compatibility with vertical farming systems, makes them particularly attractive for decentralized waste treatment models and sustainable biomass production.

BSF rearing can be implemented in fully enclosed, automated facilities that minimize contamination risks and ensure high levels of biosecurity. Furthermore, integrated insect farming within closed-loop systems allows for precise control over environmental conditions, substrate inputs, and waste outputs.

These modular and scalable designs support flexible industrial deployment in both centralized and decentralized contexts. Their tolerance to a wide range of environmental factors further reinforces their suitability for diverse operational settings. The by-product of the process, frass, is rich in nutrients and can be valorized as an organic fertilizer, contributing to the circularity of the system.

Although a higher moisture content in organic waste enhances larval growth rates, levels exceeding 80% significantly hinder the separation of frass from the black soldier fly larvae biomass through sieving techniques (*Cheng et al., 2017*).

This biological efficiency and operational flexibility have stimulated increasing interest in the downstream applications of BSF larvae, both as animal feed and, more recently, as potential ingredients for human food. Before their use as feed or food, BSF larvae are harvested at the prepupal stage and must undergo post-harvest processing to ensure product safety and quality.

This refinement includes steps such as killing (commonly by blanching in boiling water), cleaning, sterilization, and fractionation to separate proteins and lipids as needed. To ensure shelf stability, the final products should contain less than 10% moisture and fat (*Amrul et al., 2022*). Moisture reduction is typically achieved through sun drying or controlled drying methods, while oil pressing is employed to reduce lipid content.

These processing steps are essential to produce safe, stable, and hygienic larvae-based products suitable for various applications.

COMPOSITION OF BSF LARVAE

The nutritional profile of *Hermetia illucens* larvae is a key factor driving their increasing relevance in sustainable food and feed systems. It is important to note that the primary nutritional components of BSF larvae, specifically proteins and lipids, exhibit significant variability depending on the substrates used for their rearing (*Suryati et al., 2023*).

Dried BSF larvae typically contain between 35% and 45% crude protein and 15% to 35% lipids, with variations depending on the larvae's developmental stage and the substrate on which they are reared (*Macwan et al., 2023; Muslykhah et al., 2024*). The protein fraction is rich in essential amino acids such as lysine, methionine, and threonine, providing a high-quality protein source for animal nutrition.

In addition to protein, BSF larvae contain antimicrobial peptides, the biopolymer chitin and its derivative chitosan, as well as various fatty acids (*Macwan et al., 2023; Muslykhah et al., 2024*). The average ash content of BSF larvae is approximately 82.4 g/kg, ranging from 27 g/kg to 132 g/kg, which is higher than that of conventional soybean meal (71.9 g/kg) but lower than fishmeal (171.5 g/kg). The crude fiber content averages 95.4 g/kg, with a range between 41 g/kg and 213 g/kg, exceeding the crude fiber found in soybean meal (74.3 g/kg) and being substantially greater than that of fishmeal (2.6 g/kg). The average chitin content is 61.7 g/kg, varying between 38.7 g/kg and 72.1 g/kg (*Lu et al., 2022*).

BSF larvae oil consists mainly of triglycerides and phospholipids, with relative proportions influenced by diet and rearing conditions (*Tognocchi et al., 2024*). It typically contains less than 0.5% free fatty acids and is rich in saturated fatty acids, particularly lauric, palmitic, myristic, and stearic acids, alongside monounsaturated fatty acids synthesized by the larvae (*Muangrat and Pannasai, 2024*).

Lauric acid is associated with immunomodulatory effects, including anti-inflammatory, antimicrobial, and antioxidant properties, making it valuable in skin treatments, medicines, and cosmetics. While total fat content depends on the larvae's diet, the fatty acid profile remains relatively stable under consistent rearing conditions (*Quigley et al., 2025*). Beyond their high protein and lipid content, BSF larvae are rich in essential micronutrients and bioactive compounds, enhancing their value as sustainable, nutrient-dense feed ingredients (*Cruz et al., 2023*). Notably, they provide elevated levels of calcium (Ca), phosphorus (P), zinc (Zn), and iron (Fe), with a calcium-to-phosphorus ratio particularly well-suited to the dietary requirements of monogastric animals such as poultry and aquaculture species.

When compared to conventional protein sources like fishmeal, soybean meal, and meat by-products, BSF larvae biomass offers competitive or superior nutritional qualities. Although fishmeal contains a slightly higher protein content, BSF larvae provide advantages in fat quality, especially due to their lauric acid content, as well as sustainability and independence from overexploited marine resources. In contrast to soy protein, BSF larvae deliver a more balanced amino acid profile and circumvent environmental issues related to land-use change and deforestation.

Table 2

Comparative nutritional profile of BSF larvae and other protein sources (per 100g dry matter)

(*Authors' own elaboration*)

Parameter	BSF Larvae	Fishmeal	Chicken meat	Soy protein
Protein (%)	35–45	60–72	27–30	36
Lipid (%)	15–35	8–12	14	18
Lauric acid	High (up to 50% of total fat)	Absent	Low	None
Calcium (mg)	150–250	50–80	10–15	200
Phosphorus (mg)	180–240	1,200–1,500	200	550
Zinc (mg)	5–8	2–4	1.5	3
Iron (mg)	5–10	2–4	1	9
Essential amino acids	Complete set	Complete set	Complete set	Low in methionine
Sustainability	High – waste-based	Medium – marine stock depletion	Medium – land use	Low – deforestation risk

The chemical composition of BSF larvae is strongly influenced by rearing conditions such as substrate type and quality, temperature, moisture, light exposure, and larval density. Protein content generally increases when larvae are fed substrates rich in nitrogen, whereas lipid content varies with carbohydrate availability (*Tognocchi et al., 2024*). Environmental factors also affect developmental rates and nutrient accumulation; for example, suboptimal temperatures can slow development but reduce biomass yield and nutrient density (*Muangrat and Pannasai, 2024*).

Understanding and optimizing these parameters is essential to tailor BSF larvae production to specific nutritional goals, whether for animal feed or future food-grade applications. The values presented in Table 2 are indicative and may vary depending on raw material origin, processing methods, and analytical techniques. BSF larvae are distinguished by their high lauric acid content, which is absent in conventional protein sources.

Although fishmeal offers a higher protein concentration, its sustainability is increasingly challenged due to pressure on marine ecosystems. Soy protein lacks certain essential amino acids, particularly methionine, and its production is associated with deforestation risks. BSF larvae production, based on organic waste streams, offers a circular and environmentally sustainable alternative.

BSF LARVAE AS FEED: USE, BENEFITS, AND REGULATIONS

Although more than 2,000 insect species are considered edible and traditionally consumed by humans across 113 countries, not including the western nations (*Tao and Li, 2018*), only a limited number have been extensively studied for their potential use as feed in livestock and aquaculture systems. Among the most researched species are the yellow mealworm (*Tenebrio molitor* L., Coleoptera: Tenebrionidae), the black soldier fly (*Hermetia illucens* L., Diptera: Stratiomyidae), and the house fly (*Musca domestica* L., Diptera: Muscidae) (*Meneguz et al., 2018*).

Over the past 30 years, the black soldier fly has gained significant attention as a sustainable and nutritious alternative protein source in animal feed formulations. The protein meal, oils, and other by-products derived from BSF larvae processing represent valuable ingredients for animal feed. BSF larvae are considered safe for animal consumption as they are free from pests and do not bioaccumulate mycotoxins or pesticides (*Raksasat et al., 2020*).

While historically there has been some social hesitation regarding the use of insects in animal feed, this stigma has substantially diminished recently due to increased awareness of their sustainability and safety, leading to growing acceptance within livestock and aquaculture industries.

The inclusion of BSF larvae in animal feed offers multiple benefits, including reducing the risk of diseases transmitted by animals, enhancing overall health and growth performance of livestock, and significantly lowering the costs associated with animal production (*Nyamuhirwa et al., 2025*).

Dry edible insects provide between 50% and 80% of the protein required for animal nutrition. The primary target species for BSF larvae use include poultry, swine, beef, and aquaculture. Numerous studies have demonstrated both nutritional and functional benefits of BSF larvae in these diets. BSF larvae offer a balanced amino acid profile, high-quality lipids, especially antimicrobial lauric acid, and bioactive compounds that support animal health, growth performance, and immune function.

The oil extracted from BSF larvae represents a potentially more sustainable alternative to palm and coconut oils, which are commonly used in calf milk replacers worldwide (*Quigley et al., 2025*). The sustainability of palm and coconut oils is increasingly debated, particularly in the European Union, due to serious concerns including deforestation, biodiversity loss, destruction of rainforest habitats for endangered species, land clearing by fire, and displacement of local communities in palm-growing regions (*Oosterveer, 2020*).

In aquaculture, BSF larvae protein has been successfully incorporated into diets for species such as species such as tilapia, freshwater prawns, catfish, shrimp, and other omnivorous fish. Studies have demonstrated that BSF larvae meal plays a multifaceted role in supporting the health and performance of culturable aquatic species.

BSF larvae meal has been shown to regulate survival and growth rates, enhance both specific and non-specific immune responses, and improve disease resistance against a range of pathogens. In addition, it contributes to the modulation of intestinal microbiota, promoting a more balanced and functional gut environment. Several investigations have also reported that dietary inclusion of BSF larvae meal can improve the expression of genes related to growth and immunity, further underlining its potential as a functional feed ingredient in aquaculture systems (*Bruni et al., 2020; Mohan et al., 2022*).

In swine and poultry nutrition, BSF larvae-based feeds contribute to improved gut health and nutrient absorption. BSF larvae is a valuable feed component for pigs because of its high fat content and protein composition, including a well-balanced amino acid profile tailored to swine nutritional requirements (*Oh et al., 2024*).

Inclusion of BSF larvae in pig diets has not been shown to adversely affect growth performance, feed intake, nutrient digestibility, or intestinal morphology. In some cases, positive effects have been observed, such as improved growth rates, enhanced feed conversion ratios, and beneficial shifts in caecal microbiota composition (*Biasato et al., 2020*; *Yu et al., 2020*). Furthermore, pigs demonstrate a strong preference for live BSF larvae, exhibiting high motivation to interact with and consume them compared to other feed or enrichment options (*Ipema et al., 2021*).

Feeding trials have shown that BSF larvae can partially or fully replace traditional protein sources such as soybean and maize meals without compromising growth rates or feed conversion ratios. Soybean-based feeds can be entirely substituted with BSF larvae meal and fats in diets of high-performing laying hens (*Xin et al., 2024*). BSFL supplementation (50%) or total replacement of soybean cake in the diets of laying hens had no impact on hen health or performance and little to no effect on the eggs themselves (*Maurer et al., 2016*). BSF larvae oil represents a sustainable and nutrient-dense alternative in poultry and broiler chicken diets, contributing to enhanced meat quality, improved blood profiles, and beneficial impacts on muscle metabolism (*Somparn et al., 2024; Srikha et al., 2024*). However, due to nutritional variations among larvae derived from different sources, the quality of the insect material must be carefully evaluated before use (*Heuel et al., 2021*).

The use of BSF larvae as feed for ruminants has shown limited success, primarily due to their high chitin and fat content, which negatively affect ruminal fermentation and nutrient digestibility (*Jayanegara et al., 2017*). However, studies have shown that BSF-derived fat can be successfully incorporated into the diets of dairy cows, resulting in improved milk yield and quality, likely due to enhanced digestive efficiency and strengthened immune function (*Nekrasov et al., 2022*). Beyond livestock and aquaculture, BSF larvae are increasingly used in pet food formulations for companion animals such as dogs and cats.

The insect-derived proteins are hypoallergenic and easily digestible, making them suitable for animals with sensitivities to conventional protein sources. Additionally, the presence of lauric acid and other beneficial lipids supports digestive health and may have antimicrobial effects (*Freel et al., 2021; Li et al., 2024*). Dried whole black soldier fly larvae have been shown to support gestation, lactation, and growth in cats when included in their diet (*Banks et al., 2025*). Products containing BSF larvae protein include dry kibble, treats, and nutritional supplements, with growing market acceptance driven by environmental sustainability and functional benefits. BSF larvae can also be processed into soft gel capsules for cats, dogs, rabbits and other pets, offering a convenient and palatable source of high-quality proteins and essential fatty acids, including omega-3, omega-6, and omega-9, which support skin and coat health, immune function, and overall well-being.

BSF larvae oil

Whole dried BSF larvae

BSF larvae fish food

BSF larvae gel capsules

Dried mealworms from BSF larvae

Dried BSF larvae for chicken

BSF proteic bar for dogs

Dog food with BSF larvae

Fig. 2 - Various BSF larvae-derived products for animal feed

The regulatory framework in the European Union regarding insect-derived proteins has evolved progressively over recent years. Initially, Regulation (EU) 2017/893 authorized the use of processed animal proteins (PAPs) derived from insects exclusively in aquaculture feeds, marking the first significant step toward integrating insect proteins into animal nutrition.

Subsequently, this authorization was expanded by Regulation (EU) 2021/1372 to include poultry and swine feeds, reflecting growing confidence in the safety and efficacy of BSF larvae products for these livestock species. Despite these approvals, the regulations impose stringent conditions to ensure feed safety.

A crucial requirement is the strict prohibition of substrates containing catering waste or materials of animal origin for larval rearing, as these pose risks related to transmissible spongiform encephalopathies and other contaminants.

Consequently, BSF larvae must be reared exclusively on substrates derived from plant-based or non-animal organic waste streams, such as vegetable residues, manure-free food processing by-products, or agricultural waste.

These measures collectively aim to safeguard animal health while promoting sustainable and safe use of insect-derived proteins within the European Union feed industry.

Under European Union's regulations, insects may only be reared on substrates of vegetable origin or on specifically authorized materials of animal origin, such as fishmeal and hydrolyzed proteins derived from non-ruminants. Furthermore, substrates must exclude manure, catering waste, and other prohibited waste materials (*Lähteenmäki-Uutela et al., 2021*).

In some regions, however, regulations governing the safety of substrates used for insect rearing may not be as stringent as those enforced by the European Union. According to experts, the primary obstacle preventing the global development of the insect production sector is the stringent regulatory framework imposed by the European Union (*Van Huis & Gasco, 2023*).

Compliance with Regulation (EC) No 183/2005 on feed hygiene and Regulation (EC) No 767/2009 on the marketing and use of feed ensures traceability and quality control throughout the production chain. Additionally, insect producers must follow Good Manufacturing Practices (GMP) and Hazard Analysis and Critical Control Points (HACCP) principles to minimize contamination risks.

Adherence to these legislative frameworks is essential for commercial BSF larvae producers to guarantee product safety, regulatory approval, and market acceptance within the European Union. It is important to note that, initially, insect proteins were not universally authorized for all farmed animal species but only for specific uses; the authorization process and conditions vary depending on the target animal species and feed category.

BSF LARVAE AS FOOD FOR HUMANS: POTENTIAL AND CHALLENGES

Black soldier fly larvae contain approximately 42–45 g of crude protein per 100 g of dry matter (*Miron et al., 2019*), including all essential amino acids required in the human diet (*Montevecchi et al., 2021*). Therefore, BSF larvae represents a promising and nutritionally complete protein and lipids source for applications in the food industry (*Smetana et al., 2016; Miron et al., 2023a*).

To harness these nutritional benefits, BSF larvae can be processed through specific extraction steps to obtain protein and lipid-rich ingredients suitable for food applications (Figure 3).

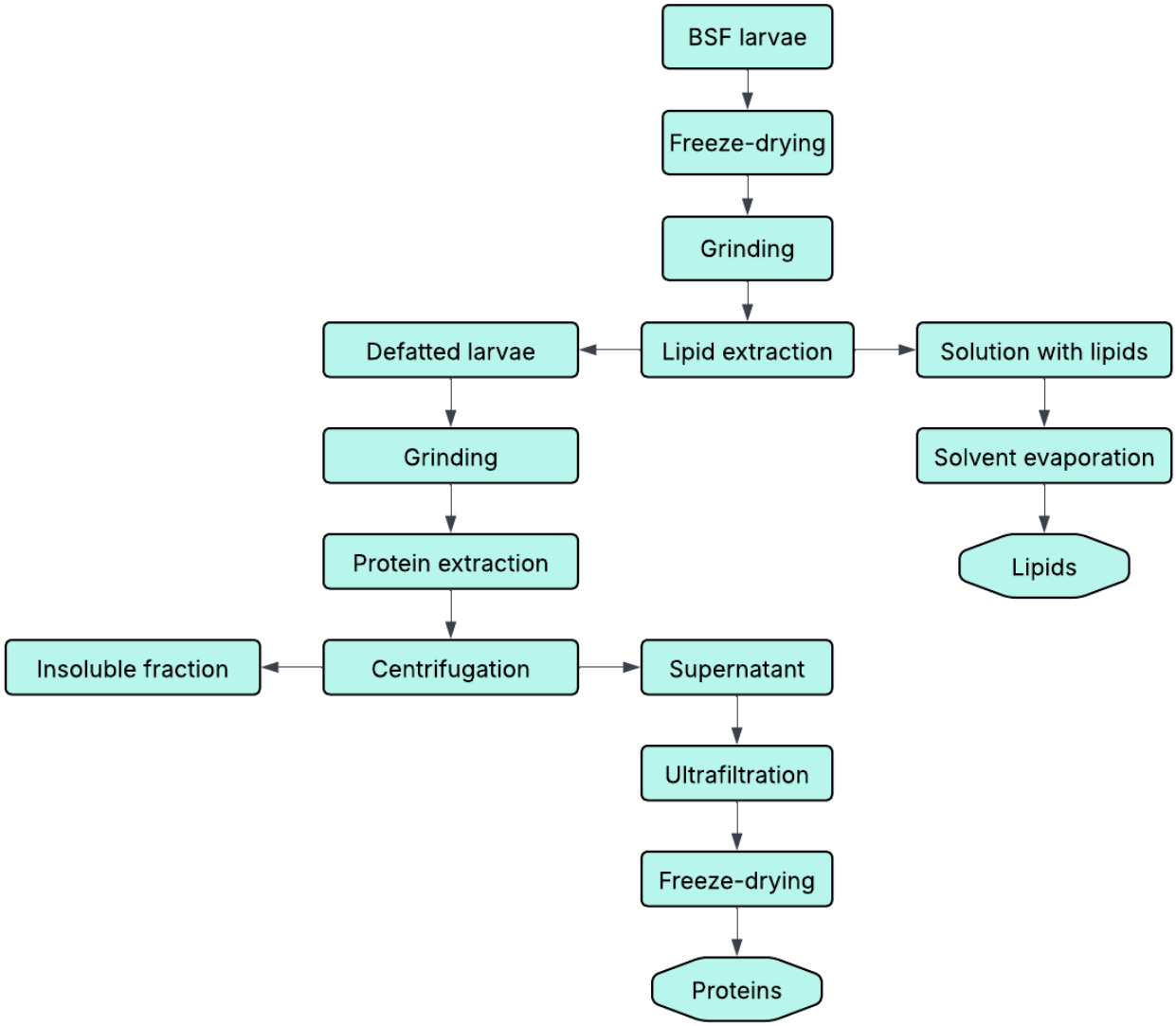

Fig. 3 - Flow diagram of protein and lipid extraction from black soldier fly larvae
(adapted from Miron et al., 2023a, under the terms of under the CC BY-NC-ND 4.0 license)

Several BSF larvae-derived products for human consumption have been developed or proposed, including dried snacks, protein powders, oils, and fermented forms, as well as their incorporation into familiar foods such as pasta, biscuits, protein bars, sausages, or protein-enriched flours used in baking and meal fortification. Insects have even been proposed as a viable protein source for space missions.

Researchers in China, Japan, and the United States are actively exploring the potential of insects as sustainable nutrition options for astronauts during space travel and aboard space stations (*FAO, 2013*).

BSF protein bar | BSF larvae oil | BSF larvae snacks (Life Origin) | Roasted BSF larvae

Fig. 4 - BSF-larvae derived products for human consumption

The commercial production and availability of farmed insects have experienced the most rapid expansion in South-East Asia, particularly through the development of cricket farming, which began in Thailand and has subsequently spread to neighboring countries such as Laos and Cambodia. Despite this

growth, national food consumption data in Thailand do not specifically categorize edible insects, although several insect species are included in national food composition tables across South-East Asia and select African countries (*EFSA, 2015*). Among the edible insect species gaining attention, BSF larvae are increasingly consumed in certain Asian countries, notably Vietnam and Thailand, where entomophagy is culturally embedded and traditionally practiced. BSF larvae are typically prepared through washing and boiling or roasting and are either consumed whole or incorporated into composite dishes such as soups, stir-fries, and snacks.

In addition to these methods, sun-drying and deep-frying are employed in some regions to enhance shelf life and flavor. In addition to direct consumption, BSF larvae are also processed into fermented products or ground into pastes used to fortify sauces and condiments with added nutritional value.

In Thailand, for example, BSF larvae are sometimes transformed into protein-rich powders, which are incorporated into noodles, rice-based products, or used as seasoning. Larval oil, extracted via mechanical pressing or solvent-based techniques, is utilized in culinary applications or as a dietary supplement, owing to its high lauric acid concentration and associated antimicrobial benefits. In Malaysia, BSF larvae are consumed raw alongside tapai, a traditional fermented beverage, with the larvae being collected from the fermented tapioca used in its production (*Wang and Shelomi, 2017*).

Although not yet widely adopted, these practices underscore a growing consumer interest in sustainable and nutrient-dense protein alternatives. BSF larvae appeal both through their rich nutritional profile, high in protein, lipids, and micronutrients such as calcium, iron, and zinc, and through their pleasant umami flavor and crunchy texture when roasted or fried.

Despite cultural familiarity with entomophagy in many Asian societies, BSF larvae remain less commonly consumed than more traditional edible insects such as crickets or silkworm pupae. However, interest in BSF is increasing due to its efficiency in organic waste conversion and superior nutrient profile, particularly in areas where food security and sustainability are pressing concerns.

As a result, BSF is gradually being incorporated into local food systems, both in rural settings and through urban initiatives promoting alternative proteins. Some small-scale food enterprises and agricultural cooperatives have started developing BSF-based food products aimed at school meals or nutritional programs, especially in regions affected by undernutrition.

Although crickets are widely consumed in many Asian and African countries, where entomophagy is culturally accepted and long practiced, in the European Union and other Western regions, the idea of farming and eating insects is still met with skepticism.

Nevertheless, interest is slowly growing. In Europe, several cricket farms have emerged in countries such as the Netherlands, Belgium, and Finland, focusing on the production of cricket powder and snacks for human consumption. At the same time, in highly developed countries such as Canada and the USA, several organic-certified farms have been established to raise crickets for food, offering products like roasted crickets, cricket powder, and frozen crickets.

These developments indicate a growing acceptance and commercialization of edible insects in both traditional and non-traditional regions, paving the way for exploring other insect species such as the BSF for both feed and food purposes.

A few innovative start-ups have emerged in Europe, attempting to introduce BSF-based foods through rebranding strategies that emphasize their nutritional and ecological advantages.

One of the key barriers to acceptance in Western cultures is the strong sense of disgust and the persistence of social taboos associated with eating insects, mainly because insects have never played a substantial role in Western food culture (*FAO, 2013; Bessa et al., 2020*). However, this perception may slowly shift due to increased awareness of the environmental benefits of insect farming, as well as rising concerns about food security and the ecological impact of conventional livestock production.

The presence of BSF larvae in pet food and animal feed, already authorized in the European Union, has contributed indirectly to increasing familiarity with the species. This growing exposure, particularly through pets, may help reduce the psychological distance between humans and insect-based products, potentially enhancing future acceptability.

Consumers are generally more willing to accept insect-based foods when insects are incorporated in processed or invisible forms, rather than presented whole (*Bußler et al., 2016; House, 2016*). Using water-soluble insect proteins in food formulations is a particularly effective strategy, as it helps reduce the visibility of the insect origin and may ease the psychological barriers related to entomophagy.

Beyond consumer perception, these soluble proteins have demonstrated valuable techno-functional properties, such as foaming and gelation, making them suitable as food additives (*Laroche et al., 2019; Dharani et al., 2025*). One promising application of insect-derived proteins is in the development of meat analogues, which are designed to replicate the sensory and, in some cases, chemical attributes of traditional meat (*Joshi & Kumar, 2015*).

These products typically include ingredients like soy protein, wheat gluten, mushrooms, legumes, algal proteins (*Jones, 2016*), and increasingly, insect proteins (*Azzollini et al., 2019*), often combined with fats and flavorings to mimic the taste and texture of meat or seafood (*Kyriakopoulou et al., 2019*).

From a legal standpoint, the consumption of BSF larvae in the European Union falls under the scope of Regulation (EU) 2015/2283 on Novel Foods, adopted in November 2015, which governs the authorization of food products without a significant history of consumption within the European Union before 1997 (*de Boer and Bast, 2018; Lähteenmäki-Uutela et al., 2021*).

The European Food Safety Authority's 2016 guidance document further elaborates on the criteria necessary for novel food approval, encompassing data on composition, production methods, toxicological and allergenic potential, and anticipated levels of human exposure (*EFSA, 2016*).

In addition to the Novel Food Regulation, several other legislative frameworks are applicable. Regulation (EC) No 852/2004 on the hygiene of foodstuffs outlines general food safety requirements, including the implementation of HACCP principles and adherence to good manufacturing practices.

Furthermore, Regulation (EU) 2017/893, although focused on the use of insects in animal feed, sets a useful precedent for the safe use of BSF larvae as a biological resource (*Lähteenmäki-Uutela et al., 2021*).

Currently, *Hermetia illucens* larvae are not included on the list of approved edible insects under the European Union's Novel Foods Regulation and therefore remain subject to the novel food authorization process for human consumption (*Miron et al., 2023b*).

While insect-based products such as *Tenebrio molitor*, *Locusta migratoria*, *Acheta domesticus*, and *Alphitobius diaperinus* have been granted authorization under the Novel Food Regulation, BSF larvae remain under evaluation, and no positive scientific opinion from EFSA has been issued to date regarding their suitability for human diets.

Consequently, the use of BSF larvae continues to be legally restricted to non-food applications, including animal feed, pet food, and fertilizers, where they are subject to strict safety, hygiene, and traceability standards.

Within the European Union, several farms and companies in countries such as France, the Netherlands, and others are already producing and marketing BSF larvae-based products intended for human consumption. These activities currently operate under specific national regulations and are subject to local food safety standards, as a unified European Union wide approval for BSF larvae as food has not yet been granted.

Despite their rich nutritional profile, several health risks associated with the consumption of BSF larvae have been reported in scientific literature. Documented adverse effects include gastrointestinal discomfort (e.g., nausea, cramps, diarrhea), often linked to microbial contamination or inadequate processing techniques.

Another important concern is the allergenic potential, particularly among individuals sensitized to crustaceans or dust mites, due to shared allergens such as tropomyosin and arginine kinase. Moreover, if larvae are reared on poorly controlled substrates, there is a risk of bioaccumulation of heavy metals or contamination with pathogens such as *Salmonella* or *Listeria monocytogenes*.

The safety of direct human consumption of BSF larvae was evaluated by examining microbial, heavy metal, and allergenic hazards. The findings indicated that blanching effectively reduced both *Escherichia coli* counts and the total viable microbial load by approximately 3 log units.

No *Salmonella* or *Listeria* species were detected. Heavy metal residues were detected but remained below established legal thresholds. However, cross-reactive allergens such as tropomyosin and arginine kinase were identified, although their clinical relevance remains to be clarified.

These results underscore the importance of proper decontamination methods, such as blanching, and highlight the influence of rearing substrates on safety outcomes (*Bessa et al., 2021*). A recent study investigated the microbiological quality of BSF larvae intended for human consumption, analyzing the effects of different rearing substrates, including those permitted by European Union regulations (cereals, fruits, vegetables) and others not permitted (e.g., co-products, nearing shelf-life or meat-based substrates).

The results highlight that substrate choice significantly influences microbial load and safety outcomes, emphasizing the need for strict monitoring and judicious selection of larval feed sources to mitigate health risks (*Brulé et al., 2024*).

To address these concerns, European Union regulations require the implementation of rigorous safety protocols, including validated thermal processing methods, full traceability of production chains, and comprehensive toxicological assessments. In practice, safe and standardized processing steps typically include blanching, drying, grinding into powder, oil extraction, and hygienic packaging. Given the allergenic potential and the novelty of insect-based foods, it is essential that products containing BSF larvae are accompanied by clear labeling and transparent consumer information to ensure safe and informed consumption.

Overall, while BSF larvae hold considerable promise as a sustainable and nutrient-dense food source, their widespread adoption for human consumption remains contingent on successfully addressing regulatory, health-related, cultural, and technological challenges.

INDUSTRIAL BSF FARMING AND COMMERCIAL PROSPECTS

In recent years, industrial-scale insect farming has grown significantly, driven by increasing demand for sustainable protein sources in both animal feed and human food sectors. In European insect production systems, species such as *Hermetia illucens* are typically reared in enclosed, controlled environments, such as boxes or cages, where key parameters like temperature, humidity, substrate composition, and water availability are precisely regulated.

When larvae represent the target harvest stage, they are grown directly on organic substrates that also serve as the medium for frass (insect waste) excretion. Egg deposition onto the substrate can occur through natural oviposition by adult flies or be facilitated manually or mechanically. Harvesting the larvae generally requires active separation from the substrate.

Furthermore, in the pre-pupal stage, BSFL naturally migrate away from the feeding substrate in search of a dry, elevated area, a behavior known as “self-harvesting”, which eliminates the need for manual collection and simplifies the harvesting process (*Wang and Shelomi, 2017*).

In small-scale or traditional farms, this is often done manually through sieving. In contrast, industrial-scale facilities employ automated systems specifically designed to optimize the efficiency of larval separation. In less industrialized systems, insects are typically deprived of feed for several hours or days before harvest to allow for gut emptying, a depuration step intended to improve hygiene. However, this procedure is not always practiced in industrial settings, where larvae usually undergo extensive post-harvest processing that may eliminate the need for prior intestinal clearance (*EFSA, 2015*).

Companies specializing in BSF larvae production have diversified their operational models, targeting various applications such as aquaculture, pet food, livestock feed, and, increasingly, human consumption. While leading producers are primarily based in Europe and North America, emerging markets are also showing increased interest and investment. Leading industrial producers such as Hexafly (Ireland),

Protix (Netherlands), InnovaFeed (France), and Agronutris (France) have established themselves as pioneers in large-scale BSF larvae production, emphasizing traceability, biosecurity, and sustainability throughout their operations.

- Hexafly (Ireland) is a company specialized in the industrial-scale cultivation of Hermetia illucens through vertical farming systems. The company applies circular economy principles by converting organic waste streams into high-value insect-derived products, including a protein-rich meal, insect oil, and an organic frass-based biofertilizer. Its production process is designed to operate with minimal land, water, and energy inputs, while maintaining high levels of efficiency and environmental sustainability. The resulting protein and oil are primarily targeted toward both human food and animal nutrition sectors, including aquaculture, pet food, and livestock feed, whereas the frass is utilized in agriculture as a natural soil enhancer with biostimulant properties. Through technological innovation and a zero-waste approach, Hexafly demonstrates the potential of insect bioconversion as a scalable solution to global challenges in food security, resource efficiency, and sustainable agriculture (*https://hexafly.com/).*

- Protix (Netherlands) operates across the entire value chain of Hermetia illucens production, from rearing larvae on carefully selected organic waste streams to processing them into high-quality

insect-based products. In its fully integrated facility, the company transforms up to 250,000 tonnes of food waste per year into valuable outputs, including up to 70,000 tonnes of live larvae equivalent. These are further processed into protein-rich meals, insect oils, fresh larvae mass, and organic fertilizers. Protix primarily supplies these ingredients to the aquaculture, pet food, and livestock feed industries, while also exploring innovative applications such as fermented insect products to improve digestibility and functionality, as well as the potential for use in human food (https://protix.com/).

- InnovaFeed (France) specializes in the industrial-scale production of Hermetia illucens larvae. Their vertically integrated operations encompass breeding, rearing, and processing larvae into high-quality insect-based products. These products include Hilucia™ Protein and Hilucia™ Oil, which are primarily utilized in aquaculture, pet food, and livestock feed sectors. Additionally, Innovafeed produces Hilucia™ Frass, a 100% natural organic fertilizer derived from insect droppings, contributing to sustainable agriculture practices. The company employs a unique industrial symbiosis model, optimizing resource efficiency and minimizing environmental impact. Innovafeed's commitment to sustainability and innovation positions them as a key player in the insect-based nutrition industry (https://innovafeed.com/en/).

- Agronutris (France) is a biotechnology company specializing in the large-scale breeding and processing of insects, particularly the black soldier fly (Hermetia illucens), mealworm (Tenebrio molitor), and cricket (Gryllodes sigillatus). Their vertically integrated operations encompass the entire value chain, from insect breeding and bioconversion of organic by-products to the production of high-quality insect-based ingredients. These include protein-rich insect meal and oils, which are primarily utilized in aquaculture, pet food, and livestock feed sectors. Additionally, Agronutris produces organic fertilizers from insect frass, contributing to sustainable agriculture practices. The company employs a circular economy model, transforming agro-industrial co-products and bio-residues into valuable nutritional ingredients, thereby reducing environmental impact and promoting resource efficiency. Their commitment to sustainability and innovation positions them as a key player in the insect-based nutrition industry. *(https://www.agronutris.com/en/).*

Together, these companies illustrate the commercial viability of BSF LARVAE farming and processing, offering a range of products, from live larvae and dried meals to specialized functional ingredients that contribute substantially to circular economy initiatives and help reduce dependence on conventional protein sources.

In the European Union, the sector continues to grow rapidly, supported by ongoing innovation, favorable policy trends, and a rising demand for alternative proteins. Countries such as France and the Netherlands are at the forefront of industrial insect farming, benefiting from strong regulatory frameworks and public-private partnerships. Romania also shows potential for development, particularly due to local interest and the availability of agri-food waste as a substrate for insect rearing.

However, the absence of specific national regulations and dedicated investment incentives remains a limiting factor for large-scale deployment. With increasing awareness of environmental sustainability, resource efficiency, and food security, BSF farming is well positioned to become a strategic sector within the emerging bioeconomy. Its potential contributions span circular agriculture, waste valorization, and innovation in both food and feed production.

CONCLUSIONS AND FUTURE DIRECTIONS

Black soldier fly (*Hermetia illucens*) larvae represent one of the most promising sustainable protein sources for both animal feed and human food applications. Their exceptional ability to convert a wide range of organic waste streams into high-quality biomass rich in protein, lipids, and micronutrients makes them ideal candidates for integration into circular bioeconomy models.

In animal nutrition, particularly in aquaculture, poultry, and swine sectors, BSF larvae have demonstrated positive effects on growth performance, feed efficiency, and immune function, while also contributing to reduced environmental impact and feed costs.

Beyond feed, BSF-derived products are increasingly explored as alternative protein sources for human consumption due to their complete amino acid profile, high lauric acid content, and techno-functional properties.

They offer opportunities for innovation in functional foods, protein supplements, and meat analogues, especially in regions facing food security challenges or resource constraints. However, despite their nutritional potential, several barriers still limit their broader adoption, particularly in Western markets. Regulatory constraints, allergenic concerns, and consumer skepticism, often rooted in cultural perceptions, remain significant hurdles.

To facilitate the mainstream use of BSF larvae in food systems, future developments should prioritize the implementation of rigorous safety protocols, standardized processing methods, and transparent labeling practices. Further research is also needed to assess long-term health risks, including allergenicity and bioaccumulation, and to provide clear scientific evidence supporting their safety.

Public education campaigns and rebranding strategies that highlight the ecological and nutritional benefits of insect-derived products can play a key role in shifting consumer attitudes.

With coordinated efforts in legislation, industry, and research, BSF larvae can contribute meaningfully to building more sustainable, resilient, and resource-efficient food systems.

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BLACK SOLDIER FLY (*HERMETIA ILLUCENS*) FOR SUSTAINABLE ORGANIC WASTE MANAGEMENT: LIFECYCLE, SUBSTRATES, AND BIOCONVERSION PARAMETERS

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MUSCA SOLDAT NEGRU (HERMETIA ILLUCENS) ÎN MANAGEMENTUL SUSTENABIL AL DEȘEURILOR ORGANICE: CICLUL DE VIAȚĂ, SUBSTRATURI ȘI PARAMETRII BIOCONVERSIEI

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Keywords: black soldier fly (BSF); insect-based organic waste treatment; food waste; municipal solid waste; sludge; agricultural residues; animal manure; bioconversion efficiency

ABSTRACT

The rapid increase in the volume of organic waste generated by households, agriculture, the food industry, and wastewater treatment facilities pose a significant challenge from both environmental and economic perspectives. Traditional waste management methods such as landfilling, composting, or anaerobic digestion are often limited by inefficiency, slow processing times, or environmental constraints. In recent years, the Black Soldier Fly (BSF, Hermetia illucens) has emerged as a highly promising species for sustainable bioconversion of various organic waste streams. This review analyzes the biological characteristics and life cycle stages of BSF larvae that enable their efficient use in waste valorization. Emphasis is placed on the types of organic substrates that can be processed and the key environmental and operational parameters influencing larval development and conversion efficiency. Critical aspects such as substrate composition, moisture, pH, larval density, and processing temperature are explored in relation to their impact on bioconversion rates. Furthermore, the environmental and economic implications of using BSF in waste management are examined, along with current challenges and future research directions. This synthesis aims to provide a solid knowledge base for optimizing large-scale bioconversion systems using BSF.

REZUMAT

Creșterea accelerată a volumului deșeurilor organice generate de gospodării, agricultură, industria alimentară și stațiile de epurare a apelor uzate reprezintă o provocare majoră atât din perspectiva mediului, cât și din cea economică. Metodele tradiționale de gestionare a deșeurilor, precum depozitarea în gropi, compostarea sau digestia anaerobă, sunt adesea limitate de eficiență scăzută, timpi mari de procesare sau restricții de mediu. În ultimii ani, musca soldat negru (BSF, Hermetia illucens) a devenit o specie extrem de promițătoare pentru bioconversia sustenabilă a diferitelor fluxuri de deșeuri organice. Această lucrare analizează caracteristicile biologice și etapele ciclului de viață ale larvelor BSF, care permit utilizarea lor eficientă în valorificarea deșeurilor. Se pune accent pe tipurile de substraturi organice care pot fi procesate și pe principalii parametri de mediu și operare care influențează dezvoltarea larvelor și eficiența conversiei. Aspecte critice precum compoziția substratului, umiditatea, pH-ul, densitatea larvară și temperatura de procesare sunt analizate în raport cu impactul lor asupra randamentului bioconversiei. De asemenea, sunt abordate implicațiile de mediu și economice ale utilizării BSF în gestionarea deșeurilor, precum și provocările actuale și direcțiile viitoare de cercetare. Această sinteză oferă o bază solidă de cunoștințe pentru optimizarea sistemelor de bioconversie la scară largă cu ajutorul BSF.

INTRODUCTION

The global generation of organic waste has reached alarming levels, posing severe environmental, economic, and social challenges. According to the most recent estimates, approximately 1.05 billion tonnes of food were wasted globally in 2022 across households, retail, and food service sectors, equivalent to 19% of all food available to consumers, or about 132 kg/person/year. Households alone were responsible for 631

million tonnes, accounting for 60% of consumer-level food waste (*UNEP, 2024a*). Similar trends have been observed in the European Union. In 2021, 58 million tonnes of food waste were recorded, of which 54% originated from households, followed by 21% from the food and beverage manufacturing sector, 9% from primary production, 9% from food services, and 7% from retail (*Statista, 2024*).

Food waste contributes to 8–10% of global greenhouse gas (GHG) emissions, almost five times the emissions from the aviation sector, and uses nearly 30% of all agricultural land (*UNCC, 2024*). The issue also aligns with SDG 12.3, which calls for halving global per capita food waste at the retail and consumer levels by 2030, and for reducing food losses along production and supply chains.

Beyond food waste, the broader organic fraction of municipal solid waste (MSW), which includes yard trimmings, paper, and other biodegradable materials, remains a major concern. MSW generation reached 2.3 billion tonnes in 2023 and, if current trends continue, is projected to rise to 3.8 billion tonnes by 2050 (*UNEP, 2024b*).

In certain urban contexts, organic waste may account for up to 70% of total MSW. When poorly managed, this fraction becomes a potent source of CH_4, a GHG over 20 times more powerful than CO_2 over a 100-year timeframe.

Other major organic residues, such as animal manure, agricultural by-products, and sewage sludge, also represent substantial sources of pollution and environmental concern, yet offer untapped opportunities for valorization through insect-based bioconversion.

These figures highlight the unsustainability of current waste management systems and reinforce the urgency of transitioning to circular, resource-efficient solutions.

In this context, bioconversion using the black soldier fly (BSF, *Hermetia illucens* (L.), Diptera: Stratiomyidae) has attracted increasing interest. BSF larvae are capable of rapidly converting various organic residues (e.g., organic fraction of municipal solid waste, food waste, manure, agricultural by-products, and sewage sludge) into protein-rich biomass, valuable lipids, and a processing residue, also called frass (*Adebayo et al., 2021; Kim et al., 2021; Mahmood et al., 2021*).

These transformations occur with relatively low environmental impacts, offering a viable path toward integrated waste valorization and nutrient recovery.

Additionally, BSF bioconversion presents significant advantages in land and water use efficiency compared to conventional livestock production and can be integrated into decentralized waste management strategies, particularly in urban or peri-urban environments, where insects offer high conversion efficiency and generate fewer greenhouse gas emissions than traditional livestock (*Mertenat et al., 2019*).

Their nutritional profile makes insects a promising option for both human food and animal feed (*van Huis and Tomberlin, 2017*). For insects to serve as effective recyclers within sustainable food systems, their production should adhere to the core principles of circular livestock farming. In this context, insects intended for human consumption should be reared exclusively on organic substrates that are unsuitable for direct human use, such as food industry by-products, unavoidable food waste, and crop residues.

Conversely, insects destined for animal feed should be raised on organic materials that are not fit for consumption by either humans or conventional livestock and aquaculture species (*Parodi et al., 2021*). This approach ensures food safety while unlocking the potential of insects as a sustainable protein source in human diets.

While bioconversion using BSF larvae offers significant promise, several restrictions and risks must be addressed. Contaminants such as heavy metals, personal care products, halogenated organic compounds, pesticides, and pharmaceutical residues, usually found in biowaste (*Brisolara and Bourgeois, 2019*), may accumulate in larvae or frass, potentially limiting their use in feed or fertilizer applications.

Pathogenic microorganisms in certain waste streams pose health risks, so effective pathogen control measures are needed during and after the bioconversion process. Regulatory constraints on the collection, processing, and utilization of organic waste and insect-derived products vary widely across regions, impacting scalability and market acceptance.

Additionally, public concerns about safety and insect rearing on waste require clear communication and strict standards for wider acceptance.

The aim of this review is to synthesize recent research on BSF-based bioconversion systems. We focus on the insect's biological characteristics, optimal rearing parameters, substrate types and conversion efficiencies, as well as the environmental, economic, and regulatory implications of scaling such systems.

By consolidating insights from multiple studies, we assess the potential and limitations of BSF bioconversion and explore how this emerging biotechnology can support the transition to circular

bioeconomy and contribute meaningfully to the achievement of global sustainability targets by 2030 and beyond.

BLACK SOLDIER FLY BIOLOGY AND LIFECYCLE

Characteristics of *Hermetia illucens*

The black soldier fly (*Hermetia illucens*) is a non-pest, non-vector dipteran species. Although it was first reported in Europe in 1926, it is native to the neotropical regions of the Americas (*Gladun, 2019; Siddiqui et al., 2022*). Its presence across the Palearctic region, including Southeastern Europe, the Middle East, Austria, Belgium, and the United Kingdom, is largely due to intentional introductions aimed at controlling housefly populations in agricultural settings such as farms and stables (*Demetriou et al., 2022*).

Its subsequent spread throughout Europe is likely facilitated by both natural dispersal (e.g., wind currents) and anthropogenic factors (e.g., human-mediated transport).

Today, BSF is a cosmopolitan species and has garnered global attention as a model organism for organic waste bioconversion, owing to its remarkable biological resilience, ecological adaptability, and economic potential.

Adult BSFs have a dark coloration and a wasp-like appearance. Lacking functional mouthparts, they do not feed during the adult stage, which eliminates the risk of disease transmission through regurgitation (*Siddiqui et al., 2022*). Their sole purpose in this stage is reproduction, which makes them well-suited for indoor or controlled rearing environments. Females typically lay eggs in dry crevices near decomposing organic matter.

The larval stage, which lasts about 14–18 days, is the most important for bioconversion. During this stage, BSF larvae are voracious consumers, capable of efficiently processing a wide variety of organic substrates. Under optimal conditions, they can reduce organic waste mass by 50–75%, while accumulating high levels of protein (up to 42%) rich in essential amino acids, lipids (up to 35%) (*Wang and Shelomi, 2017*), calcium (8%), phosphorus (1–2%), sodium (0.1–0.3%), and magnesium (0.4–1%) (*Chia et al., 2019*), depending on the feedstock. Once mature, the larvae enter the prepupal stage and seek dry environments for pupation.

BSF is highly tolerant of a broad range of environmental conditions. Its resilience, high feed conversion efficiency, and rapid development make it especially suitable for industrial-scale rearing systems. In addition to its bioconversion role, BSF also contributes ecologically by accelerating the decomposition of organic waste and suppressing populations of nuisance insects such as the common housefly through competitive exclusion.

These combined biological traits, alongside its environmental and economic benefits, position BSF as a key species in sustainable waste management and circular bioeconomy strategies.

Life cycle stages relevant for bioconversion

In natural environments, black soldier flies deposit their eggs in or near moist organic matter, providing newly hatched larvae with immediate access to a nutrient-rich substrate. After mating, females oviposit clusters of approximately 500–900 eggs per reproductive event.

Shortly after having oviposited, the female dies. BSF eggs are oval-shaped, approximately 1 mm in length, and have a yellowish-cream color that gradually darkens as they near hatching (*Raihan et al., 2023*). Eggs typically hatch within 3 to 4 days depending on environmental factors such as temperature and humidity (*Chia, 2019*).

Upon hatching, larvae begin intensive feeding on a broad range of organic substrates, including food waste, agricultural residues, and manure. The larval stage, lasting approximately 14–18 days under optimal conditions, is the most metabolically active and critical phase for bioconversion. During this period, larvae exhibit remarkable feed conversion efficiency, rapidly consuming organic matter and transforming it into valuable biomass.

Through bio-catalytic digestion, larvae convert complex organic substrates into high-value proteins and lipids, with lipids accounting for roughly 30% of their body mass. These lipid reserves are crucial for the non-feeding adult stage (*Nguyen et al., 2015*).

The larval development proceeds through six instars, each marked by specific physiological changes and increasing biomass. In adverse conditions, such as nutrient scarcity or unsuitable environmental factors, the larval stage can be extended up to six months, allowing the insect to survive until favorable conditions

return. Upon reaching full maturity, larvae enter the prepupal stage, characterized by cessation of feeding and cuticle darkening.

They actively migrate away from the feeding substrate to locate a dry and secure environment for pupation. The pupal stage, a non-feeding metamorphic phase lasting 1 to 2 weeks, transforms the larvae into an adult fly. Environmental variables including temperature, humidity, and light exposure influence the duration of this stage.

Adult black soldier flies have a brief lifespan of 5 to 8 days. Devoid of functional mouthparts and digestive organs, adults do not feed and rely entirely on energy reserves accumulated during larval development.

Their primary biological roles are reproduction, mating and oviposition, after which the cycle begins again. This non-feeding adult stage also limits disease transmission risks, making BSF suitable for controlled rearing environments focused on larval biomass production.

Understanding each stage of the BSF life cycle is essential for optimizing rearing strategies, maximizing biomass yield, and ensuring the efficiency and safety of bioconversion systems.

Figure 1 illustrates the complete life cycle of *Hermetia illucens*, from egg through larval, prepupal, and pupal stages to the adult fly.

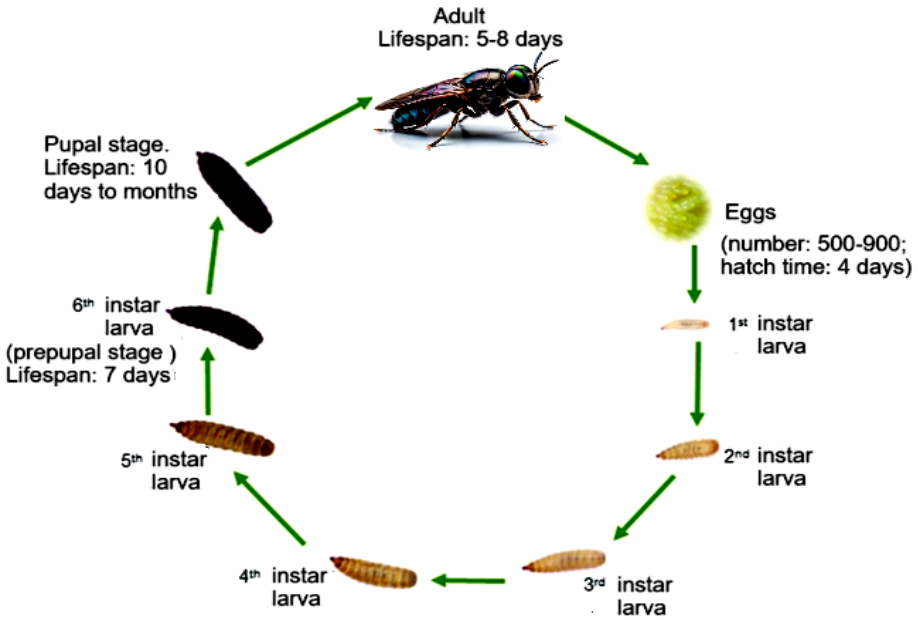

Fig. 1 - The complete life cycle of *Hermetia illucens*

(adapted from Chia, 2019, under the terms of the Creative Commons Attribution License (CC BY 4.0))

Figure 2 shows the development of larvae which were reared on chicken feed together with the corresponding mean body weight (BW) (wet weight) of at least 100 larvae; the body weight development corresponds to an 8083 fold increase from day 1 to day 18 (maximum body weight at day 18); each division of the scaling from day 1 to day 18 represents 1 mm; at day 31 the division of the scaling represents 10 mm (*Seyedalmoosavi et al., 2022*).

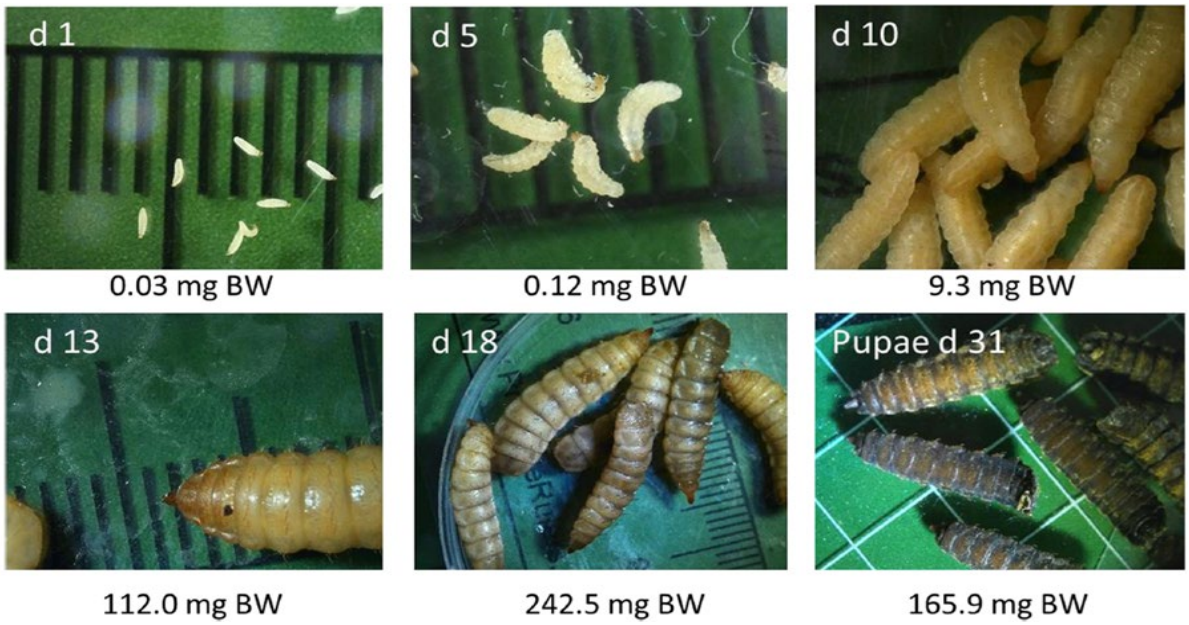

Fig. 2 - Development of BSF larvae from d 1 after hatching up to the pupal stage

(Seyedalmoosavi et al., 2022, under the terms of the Creative Commons Attribution License (CC BY 4.0)

Advantages of BSF over other insects

Other insect species, including *Acheta domestica*, *Alphitobius diaperinus*, *Gryllodes sigillatus*, *Locusta migratoria*, *Musca domestica*, *Schistocerca gregaria*, *Tenebrio molitor*, and *Zophobas morio*, have also been recognized as efficient agents for the bioconversion of organic waste (*Surendra et al., 2020*).

However, *Hermetia illucens* has recently attracted increasing attention as a superior candidate for large-scale bioconversion applications, particularly when compared to species such as *Tenebrio molitor* (mealworms), *Musca domestica* (houseflies), and various beetle larvae (*El Deen et al., 2022*).

One of BSF's major advantages lies in its exceptional substrate flexibility, being capable of converting a wide range of organic waste, such as food scraps, agricultural residues, and animal manure, into valuable larval biomass rich in protein and lipids.

This, along with its rapid biomass accumulation rate, makes BSF particularly suited for scalable waste valorization systems. In addition, BSF larvae demonstrates a high tolerance to environmental fluctuations (e.g., temperature and humidity), offering operational flexibility across different climate conditions. Their short life cycle allows for frequent harvesting and efficient production cycles.

From a sanitary perspective, BSF has clear advantages over insects like the housefly: adult BSFs do not feed and are not vectors of human pathogens, which minimizes biosecurity risks during rearing.

Another key strength is the economic and functional versatility of BSF-derived products. Larval protein can be used in animal feed for poultry, aquaculture, and pets, while the lipid fraction has potential applications in biodiesel and cosmetics. Moreover, BSF frass (a mix of larval excrement and residues) can serve as an organic fertilizer, contributing to nutrient recycling and supporting circular economy strategies.

Finally, BSF receives increasing regulatory acceptance and positive public perception. In several jurisdictions, BSF-based products have already been approved for animal feed, and others are updating legislation accordingly. This growing recognition further strengthens BSF's strategic potential in future waste management and sustainable agriculture systems.

ORGANIC WASTE TYPES USED IN BIOCONVERSION

Food waste, encompassing both edible and inedible fractions discarded at the consumer, retail, and food processing stages, is a highly heterogeneous yet nutrient-rich substrate. Its high moisture content and readily biodegradable organic compounds facilitate rapid larval growth and efficient biomass conversion by BSF larvae (*Ebeneezar et al., 2021*).

The versatility of food waste as a feedstock makes it one of the most utilized substrates in BSF bioconversion research and applications. Nevertheless, challenges arise from the variability in composition and the risk of spoilage and odor generation if not processed promptly and properly managed.

The organic fraction of municipal solid waste typically consists of food scraps, yard trimmings, paper, and other biodegradable materials collected through municipal waste management systems. This mixed organic substrate offers a substantial feedstock for BSF larvae; however, it is often contaminated with plastics, inert materials, or other non-biodegradable components that reduce process efficiency and may require pretreatment steps such as sorting or grinding (*Diener et al., 2011*).

The heterogeneity and seasonal variability of MSW organic fractions also influence larval growth performance and bioconversion yields.

Sewage sludge*,* the semi-solid by-product generated during the treatment of municipal wastewater, contains high levels of organic matter and essential nutrients such as nitrogen and phosphorus, making it a potentially valuable substrate for bioconversion.

Conventional sludge treatment can account for up to 50% of total operating costs in wastewater treatment facilities, posing a significant economic burden. Bioconversion of sewage sludge using BSF larvae emerges as a promising alternative, which not only contributes to sludge volume reduction but also generates value-added larval biomass, potentially offsetting treatment costs (*Bohm et al., 2022*).

The application of BSF larvae has also demonstrated effectiveness in reducing pathogen loads and improving the safety of residual material. However, potential contamination with heavy metals, pharmaceutical residues, or other xenobiotics remains a critical concern due to the risk of bioaccumulation.

Moreover, stringent regulatory frameworks govern the handling and use of sewage sludge and its by-products, requiring thorough risk assessment before implementation.

Agricultural residues, such as crop stalks, husks, and other lignocellulosic by-products, present a more fibrous and recalcitrant substrate for BSF larvae. While BSF can process a wide variety of organic waste, the high cellulose and lignin content of materials like straw and corn stalks limits their digestibility (*Ee et al., 2022*).

Pretreatment strategies, such as mechanical shredding, fermentation, or co-digestion with more easily degradable substrates like fruit or vegetable waste, can significantly improve larval development and bioconversion efficiency. Such interventions are essential to unlock the potential of agricultural residues as a viable feedstock for insect-based recycling systems.

Animal manure, a by-product of livestock production, is rich in nutrients and organic matter but, if mismanaged, serves as a reservoir for pathogens and a source of GHG emissions.

These risks are especially critical in areas with intensive animal husbandry, where manure production exceeds the nutrient uptake capacity of surrounding cropland. Improper handling leads to nutrient runoff, environmental contamination, and public health threats. BSF larvae show great potential in manure treatment, rapidly transforming its physical, chemical, and biological characteristics within one to two weeks (*Bortolini et al., 2020; Sanchez Matos et al., 2020*).

In addition, BSF bioconversion reduces manure odor, pathogen levels, and antibiotic resistance risks (*Beskin et al., 2018*).

BIOCONVERSION PROCESS AND PARAMETERS

The bioconversion of organic waste using BSF larvae is a complex biological process influenced by multiple interrelated parameters. Optimizing these parameters is essential to maximize larval growth, waste reduction efficiency, and the quality of the resultant biomass. BSF larvae exhibit high bioconversion efficiency, with approximately 800 grams of larval biomass produced from 4 kilograms of organic waste, corresponding to a waste reduction rate of around 75% (*Ibadurrohman et al., 2020*).

Sustainable operation of BSF larvae-based biowaste treatment facilities depends on access to diverse and high-quality organic substrates. However, many nutrient-rich waste streams are already allocated to other uses, such as animal feed or energy recovery, while inadequate waste management practices further restrict substrate availability.

Moreover, variability in the composition and supply of feedstock can disrupt daily operations and adversely affect BSF larvae performance, posing challenges to both the sustainability and scalability of this technology (*Mertenat et al., 2019*).

Substrate characteristics

The nutritional composition and physical properties of the substrate are critical determinants of the bioconversion performance of BSF larvae. Essential macronutrients such as organic matter, proteins, lipids,

non-fibrous carbohydrates, and fibers significantly influence larval development and metabolic efficiency (*Lalander et al., 2018*).

Readily digestible components, proteins, non-fibrous carbohydrates, and lipids have been shown to enhance both larval growth and conversion efficiency (*Beniers and Graham, 2019*), whereas fibrous materials like cellulose and lignin are poorly digested and typically inhibit growth (*Liu et al., 2018*). Substrate types vary substantially in nutrient content.

For example, food waste tends to be rich in lipids and easily degradable carbohydrates, making it highly favorable for larval development. In contrast, manures generally exhibit lower levels of organic matter and higher fiber content, while fruit and vegetable residues often lack adequate protein (*Gold et al., 2020*).

BSF larvae adjust their nutrient assimilation and growth dynamics in response to these compositional differences, aiming to accumulate sufficient energy reserves for metamorphosis and adult emergence.

Additionally, substrates that are high in fiber or contain inhibitory compounds can negatively impact BSF larval development and reduce conversion efficiency. This includes materials such as fruit and vegetable pulp, whole grains, grain residues, as well as those with high moisture content like expired milk, beverages, or molasses.

Substrates with unbalanced nutritional profiles may further limit larval growth. To overcome these limitations, pretreatment methods such as grinding, dilution, or homogenization are often employed to enhance substrate uniformity and improve digestibility (*Alyokhin et al., 2019*).

In addition to nutrient content, other substrate parameters such as particle size, moisture content and degradability strongly affect bioconversion outcomes. It is essential to reduce the initial substrate to particles measuring 1–2 cm in diameter, as BSF larvae are unable to break down larger particles with their mouthparts (*Basri et al., 2022*).

Moist, nutrient-rich, and easily degradable substrates, such as bakery or milling residues, are associated with higher larval biomass yields and more efficient waste reduction (*Gold et al., 2020*). However, such substrates are frequently diverted toward other valorization routes, like animal feed or energy production, reducing their availability for BSF-based treatment.

Beyond nutrient and physical characteristics, BSF larvae offer additional benefits through their capacity to mitigate contaminants present in organic waste streams. They have been shown to reduce microbial contaminants and pharmaceutical residues during the bioconversion process, while also demonstrating tolerance to microplastics and elevated levels of heavy metals in the substrate (*Bohm et al., 2022*).

Moreover, BSF larvae can assist in the removal of toxic elements such as zinc from waste streams, although high concentrations of zinc can negatively affect larval development (*Diener et al., 2011*).

Temperature

Temperature is a critical environmental factor influencing the metabolism, growth rate, and overall development of BSF larvae. Due to their high sensitivity to cold, BSF cannot survive in northwestern Europe or in regions where temperatures fall below 5 °C (*Lu et al., 2022*). *Holmes et al. (2016)* further investigated thermal tolerance and reported that BSF eggs can successfully hatch at temperatures between 12 °C and 16 °C, while larvae require a minimum of approximately 19 °C to survive.

These findings are particularly important when designing rearing systems in areas with significant temperature variability. The optimal temperature range for larval growth and development is generally between 25 °C and 30 °C (*Shumo et al., 2019; Ribeiro et al., 2022*).

Temperatures below this range slow down metabolic processes and larval development, leading to extended bioconversion periods and potentially lower biomass yields. Conversely, temperatures exceeding the optimal range may induce heat stress, increasing larval mortality and reducing conversion efficiency.

Maintaining stable temperatures within the optimal range is therefore essential to ensure effective substrate degradation, high larval biomass production, and efficient overall performance.

Additionally, deviations from these thermal limits can adversely affect the microbial communities involved in waste breakdown, thereby compromising bioconversion outcomes.

Moisture content

Maintaining optimal moisture levels within the substrate is essential for effective bioconversion by BSF larvae, as they require a moist environment to sustain feeding and development. The influence of

relative humidity (25%, 40%, 50%, 60%, and 70%) on BSF egg hatching and adult emergence showed that higher humidity levels led to increased hatching and adult emergence rates, while also slowing down the overall development time (*Holmes et al., 2012*).

The ideal moisture content typically ranges between 70% and 85%, although acceptable ranges vary from 50% to 80%, depending on substrate type (*Dortmans et al., 2021; Siddiqui et al., 2022*).

Moisture levels below this range can inhibit larval activity and reduce survival rates, while excessive moisture may create anaerobic conditions, resulting in substrate spoilage, reduced bioconversion efficiency, and odor problems. Additionally, high relative moisture positively influences the hatching success of BSF eggs and the emergence rate of adult flies, while also shortening their developmental period (*Holmes et al., 2012*).

Therefore, maintaining appropriate moisture is critical not only for larval growth but also for optimizing overall bioconversion performance and minimizing operational challenges.

Light

BSF requires adequate light exposure to initiate mating behavior. Since natural light intensity is insufficient during winter, artificial lighting becomes necessary to support reproduction. Various light sources such as fluorescent, halogen, LED, and oxo bulbs have proven effective, whereas rare earth lamps have failed to induce mating. Therefore, the choice of lighting plays a crucial role in successful BSF reproduction under controlled conditions (*Kim et al., 2021*).

Additionally, light wavelength and photoperiod can influence mating efficiency and oviposition rates. Studies suggest that UV-A and blue spectra are more stimulating for adult activity, while prolonged exposure may enhance reproductive outcomes in artificial environments.

Larval density

The initial density of BSF larvae introduced into the substrate significantly affects both waste reduction efficiency and biomass production. While higher larval densities can accelerate the rate of substrate degradation due to increased feeding activity, excessive crowding may intensify competition for nutrients, leading to reduced individual growth rates and higher mortality.

Conversely, lower densities might result in underutilization of the substrate's bioconversion potential. Optimal larval densities depend on substrate type and operational scale but typically range between 5 and 10 larvae per gram of substrate. *Barragán-Fonseca et al. (2018)* found that larval density within breeding containers influences nutrient composition, particularly crude fat content, although it does not significantly affect protein levels.

These findings suggest that managing larval density is crucial not only for maximizing biomass yield but also for modulating the nutritional quality of the larvae. Moreover, larval density can influence the microbial environment within the substrate, potentially affecting both larval health and the hygienic quality of the frass. Therefore, careful regulation of larval numbers is essential to optimize overall bioconversion performance.

Duration of bioconversion

The duration of the bioconversion process significantly influences both the degree of waste reduction and the quality of the larval biomass produced. Typically, larval development cycles range from 10 to 20 days, depending on factors such as substrate composition, moisture content, larval density, and the desired level of larval maturity at harvest.

Shorter cycles may result in incomplete substrate degradation and lower biomass yields, whereas excessively prolonged bioconversion can cause nutrient depletion in the substrate, reducing larval growth rates.

Moreover, extended rearing periods increase the risk of microbial contamination and potential spoilage, which can negatively impact both larval health and product safety.

Optimizing the duration of bioconversion is therefore essential to balance maximal waste reduction with the production of high-quality larval biomass suitable for downstream applications. In addition, the duration of bioconversion can influence the chemical composition of the larvae, including protein and lipid content, which are critical for their intended use as animal feed or bio-based products.

It also affects the characteristics of the residual frass, which may vary in nutrient content and microbial load depending on the rearing time. Therefore, defining an optimal bioconversion period is

essential not only for waste management efficiency but also for the overall quality and safety of the resulting products.

Performance metrics

Key indicators for evaluating the efficiency of BSF bioconversion include larval growth rate, individual larval weight, substrate reduction percentage, and the biochemical composition of the larval biomass, particularly protein and lipid content (*Gold et al., 2020*).

Typically, larval biomass contains 35–45% protein and 15–35% lipids, with variations largely dependent on diet composition and rearing conditions. Substrate reduction rates often exceed 50%, underscoring the substantial capacity of BSF larvae to diminish organic waste volumes effectively.

Monitoring these performance metrics is essential for optimizing process parameters and ensuring consistent production of high-quality biomass for downstream applications such as animal feed or biofuel production.

BSF larvae have been successfully employed for the treatment of various organic waste types, achieving waste reduction rates ranging between 52% and 80%, depending on the substrate, while generating a relatively high biomass yield of approximately 15% of the larval weight relative to the processed waste (*Salam et al., 2022*).

Their voracious feeding behavior allows them to consume up to four times their body weight in organic matter per day, depending on the biowaste composition (*Liu et al., 2018*).

For instance, in the case of food waste, a 14-day bioconversion process resulted in a substrate reduction of 52% and a bioconversion ratio of 28% (dry matter basis) (*Ermolaev et al., 2019*). BSF is considered only moderately effective in biodegrading nutrient-poor substrates such as fruit and vegetable pulp (*Smetana et al., 2019*).

Although fruit and vegetable waste tend to slow larval growth and result in lower waste conversion efficiency compared to mixed food waste (*English et al., 2021*), it may offer the advantage of higher EPA and DHA content relative to other land-based substrates. In poultry farms, BSF larvae have been shown to reduce manure accumulation by up to 60%, with approximately 56% of chicken manure mass being converted into protein- and fat-rich larval biomass suitable for animal feed (*Newton et al., 2005 a*).

Similar outcomes have been documented for dairy and pig manure, with reduction rates of approximately 58% and 56%, respectively (*Newton et al., 2005 b; Myers et al., 2008*). Although animal manure can be effective for waste reduction, its use in large-scale BSF larvae production is limited by the significantly longer development time from hatching to the prepupal stage compared to other feed sources (*English et al., 2021*).

Additionally, BSF larvae have demonstrated the capacity to process lignocellulosic agricultural residues, achieving reduction rates of 32% for rice straw and 49% for corn straw (*Gao et al., 2019*). The effectiveness of waste reduction is strongly dependent on the physico-chemical characteristics of the substrate. Blended waste streams, consisting of multiple organic waste types, tend to yield higher reduction rates than single-stream inputs. This may be attributed to synergistic effects that enhance both larval enzymatic digestion and the microbial activity associated with bioconversion (*Nyakeri et al., 2017*).

COMPARISON WITH CONVENTIONAL TREATMENT METHODS

Bioconversion using BSF larvae offers a biologically driven alternative to traditional organic waste management strategies, including landfilling, composting, and anaerobic digestion.

Compared to landfilling, BSF bioconversion significantly reduces the volume of waste diverted to landfill sites, thereby mitigating long-term environmental risks such as soil and groundwater contamination and GHG emissions, particularly methane, a potent contributor to climate change.

When compared to composting, BSF treatment achieves faster waste reduction rates and produces valuable larval biomass rich in proteins and lipids, which can be utilized as animal feed or for other high-value products. Composting primarily yields stabilized organic matter intended as soil amendment but does not generate such nutrient-dense biomass.

Relative to anaerobic digestion, BSF bioconversion generally requires shorter processing times and results in lower GHG emissions due to the aerobic feeding activity of the larvae, whereas anaerobic digestion produces methane and other gases during organic matter breakdown.

Additionally, the larval biomass produced can offset reliance on conventional protein sources in feed industries, offering economic benefits not attainable through anaerobic digestion alone.

Despite these advantages, integration of BSF bioconversion into existing waste management frameworks necessitates overcoming operational challenges, such as ensuring a consistent substrate supply and meeting regulatory standards. Hybrid approaches combining BSF larvae treatment with composting or anaerobic digestion may optimize resource recovery, reduce environmental footprints, and enhance circular bioeconomy outcomes.

Moreover, BSF bioconversion operates effectively at small to medium scale with minimal land footprint and energy input, making it suitable for decentralized waste management systems, especially in urban or remote settings.

Table 1

Comparative overview of conventional organic waste treatment methods vs. BSF bioconversion

(Authors' own elaboration)

Aspect	Landfilling	Composting	Anaerobic digestion	BSF bioconversion
Duration	Years	Weeks to months	Weeks	10–20 days
Waste volume reduction	Moderate	High	High	High (50–80%)
GHG emissions	Very high (CH_4, CO_2)	Moderate	High (CH_4)	Low (minimal CH_4)
End products	Landfilled waste	Soil amendment	Biogas and digestate	Protein- and lipid-rich larvae biomass, frass fertilizer
Economic value	Negative (management and environmental costs)	Low (low-value amendment)	Moderate (valuable biogas)	High (valuable biomass for feed and other applications)
Health Impact	Risks of contamination and disease vectors	Low	Controlled	Low (non-disease vector species)
Scalability	Large scale	Large scale	Large scale	Growing, dependent on logistics and regulations

ENVIRONMENTAL AND ECONOMIC ASPECTS

Energy efficiency and greenhouse gas emissions

Bioconversion using BSF larvae has demonstrated significant environmental benefits compared to conventional organic waste treatment methods. The process is energy-efficient, requiring relatively low inputs for larval rearing compared to energy-intensive technologies such as incineration or anaerobic digestion.

Moreover, BSF bioconversion substantially reduces GHG emissions by diverting organic waste from landfills, where anaerobic decomposition produces CH_4, a potent GHG. Integrating BSF larvae treatment can lower the overall carbon footprint of organic waste management systems, contributing to climate change mitigation efforts.

Insects represent a rich source of proteins and lipids, positioning them as a promising sustainable protein alternative for both human and animal consumption in the future (*Spranghers et al., 2017*). Their primary advantage compared to traditional livestock production lies in their significantly reduced environmental footprint when scaled to industrial levels (*Bosch et al., 2019*).

Insects exhibit a more efficient feed-to-protein conversion ratio relative to cattle, swine, and in some cases, poultry (*Oonincx and van Loon, 2015*). Industrial-scale insect farming demands considerably less water and land area than conventional animal husbandry, particularly when organic waste streams are utilized as feed (*Allegretti et al., 2018*).

Furthermore, insect rearing results in lower emissions of GHG and ammonia. Life-cycle assessments evaluating the environmental sustainability of insect-derived protein for feed and food applications indicate that insect-based protein powders or meat substitutes may offer an environmental benefit approximately two to five times greater than that of conventional meat products.

Operational and sanitary benefits in waste management

From a waste management perspective, employing BSF for organic waste treatment brings multiple environmental and operational benefits beyond conventional processing methods. These include rapid waste volume reduction, efficient transformation of organic residues into high-value larval biomass and enhanced on-site hygiene.

Unlike other insects, BSF is not associated with disease transmission, making it a biologically safe species for use in controlled waste systems. Moreover, BSF larvae actively suppress pathogenic microorganisms and outcompete other nuisance pests, improving overall sanitary conditions.

A notable advantage is their capacity to reduce malodorous compounds generated by animal manures. *Beskin et al. (2018)* reported odor mitigation rates of up to 87% in poultry, swine, and dairy waste. These attributes make BSF a practical option for improving environmental hygiene in decentralized and small-scale waste facilities.

Economic costs and benefits

From an economic perspective, BSF bioconversion offers promising opportunities. The process converts low-value organic residues into high-value products, such as protein-rich larvae and nutrient-dense frass, which can generate revenue streams in animal feed and fertilizer markets. Initial investments include infrastructure for rearing facilities, substrate preparation, and processing equipment, but operational costs are generally lower compared to chemical or thermal treatments.

Profitability depends on factors like scale, substrate availability, and market demand for insect-derived products. Pilot projects and commercial operations worldwide are increasingly demonstrating the financial viability of BSF bioconversion in circular bioeconomy contexts.

CURRENT CHALLENGES AND RESEARCH GAPS

Despite the growing interest in *Hermetia illucens* as a sustainable solution for organic waste bioconversion, several challenges still hinder its large-scale implementation and full integration into circular bioeconomy models. Scalability remains one of the most pressing obstacles.

While laboratory and pilot-scale studies have demonstrated the efficiency of BSF larvae in converting diverse organic substrates, upscaling the process to industrial levels poses technical and economic difficulties. Factors such as space requirements, automation of larval handling, feedstock logistics, and climate control have become increasingly complex in high-volume facilities.

Moreover, maintaining consistent bioconversion efficiency across variable waste streams remains a technical challenge under commercial conditions.

Emerging risks associated with pathogen transfer, heavy metals, and chemical residues must be closely monitored when rearing BSF larvae on waste substrates. Continuous risk assessment and robust biosecurity protocols are crucial to ensure product safety. Harmonized international regulations are urgently needed to facilitate trade and attract investment in BSF technologies.

However, legislative and regulatory barriers remain a major challenge. In many regions, insects are still ambiguously classified, and the use of substrates like manure or sewage sludge is restricted or lacks clear legal guidance. Within the EU, specific organic waste streams such as food waste and animal manure are subject to regulatory constraints (*Lalander and Vinnerås, 2022*).

Moreover, end-products like insect protein and frass face varying safety and quality standards across markets. Clear, science-based guidelines and legal definitions are needed to support the safe and sustainable scaling of BSF-based systems. Encouraging collaboration between researchers, policymakers, and industry stakeholders is key to overcoming these regulatory hurdles.

Social acceptability and public perception represent additional hurdles, especially in regions where the use of insects in food chains or waste management is culturally unfamiliar or stigmatized. Public awareness campaigns and transparent risk communication strategies are essential to foster acceptance and ensure market uptake of insect-derived products.

Finally, there is a pressing need for process standardization and harmonization of evaluation metrics. Variability in experimental designs, feedstock types, larval densities, and performance indicators across studies makes it difficult to compare results and formulate best practices.

Establishing standardized protocols for BSF larvae rearing, waste treatment efficiency, and product quality assessment is crucial for the scientific advancement and industrial scalability of this technology.

Additionally, long-term environmental impact assessments and techno-economic analyses are lacking, which hinders full understanding of sustainability profiles and investment risks associated with BSF larvae bioconversion. Addressing these research gaps will support evidence-based policy making and business development.

A summary of these key challenges and their potential mitigation strategies is provided in Table 2.

Table 2

Key challenges in BSF larvae-based organic waste bioconversion systems

(Authors' own elaboration)

Challenge	Description	Potential solutions
Scalability	Difficulty in upscaling BSFL systems due to technical constraints (e.g., automation, space, climate control) and cost of operations.	Development of modular, automated systems; optimization of process parameters for industrial scale.
Regulatory barriers	Ambiguous or restrictive legislation regarding insect farming, substrate types (e.g., sludge, manure), and product safety.	Clear legal frameworks; harmonization of regulations across regions; safety protocols for feed/product.
Social acceptance	Cultural resistance or lack of public trust in insect-based waste management and insect-derived products.	Public awareness campaigns; education; transparency in production and safety standards.
Standardization	Inconsistent methodologies, metrics, and performance indicators across studies and facilities.	Establishment of standardized protocols for rearing, efficiency assessment, and product characterization.

Despite these multifaceted challenges, the potential of BSF larvae bioconversion remains substantial. Continued interdisciplinary research, supported by targeted funding and inclusive policy development, will be essential to unlock scalable and safe applications.

Advancements in biotechnology, engineering, and waste management practices are expected to enhance system robustness and efficiency. If these obstacles are systematically addressed, BSF-based systems could become a cornerstone of future circular bioeconomies, contributing simultaneously to waste reduction, resource recovery, and sustainable food and feed production.

CONCLUSIONS AND PERSPECTIVES

The BSF has demonstrated significant potential as a sustainable and efficient bioconversion agent for a wide range of organic waste substrates. Its remarkable capacity to transform diverse residues, including food waste, animal manure, sewage sludge, and agricultural by-products, into valuable biomass, lipids, and frass positions as a promising tool for integrated waste valorization within circular bioeconomy frameworks.

The process is highly influenced by factors such as substrate moisture content, nutrient composition, larval density, and ambient conditions, which must be carefully controlled in scaled-up systems. BSF-based systems offer considerable environmental benefits, such as reduction of greenhouse gas emissions, decreased reliance on conventional protein sources, and nutrient recycling through organic fertilizer production.

However, to fully realize the potential of BSF bioconversion on an industrial scale, further research is required to address existing challenges.

Priority areas include optimizing large-scale rearing protocols, ensuring feedstock safety and consistency, and establishing harmonized regulatory frameworks that facilitate commercialization while safeguarding public health. Moreover, comprehensive life cycle assessments and techno-economic analyses are needed to strengthen the evidence base and promote sustainable implementation globally.

Looking ahead, BSF bioconversion is poised to play a pivotal role in the future of organic waste management, particularly as global waste volumes continue to rise and sustainability targets become more urgent. Integration of BSF technologies into decentralized and urban waste treatment systems can enhance resource efficiency and contribute significantly to achieving SDGs, especially SDG 12.

Continued interdisciplinary collaboration between researchers, policymakers, and industry stakeholders will be essential to accelerate innovation, improve acceptance, and scale up this promising biotechnology for a more sustainable and circular future.

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THE EFFECTS OF PRUNING SHEAR DESIGN ON HAND FORCES DURING HAZELNUT SUCKERS CUTTING

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FINDIK SÜRGÜNLERININ KESIMI SIRASINDA BUDAMA MAKASI TASARIMININ EL KUVVETLERI ÜZERINDEKI ETKILERI

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ABSTRACT

This study was conducted to comparatively evaluate the cutting force requirements and design characteristics of ten different pruning shears during hazelnut sucker cutting. Hazelnut suckers were used as the plant material, and cutting tests were performed using a Lloyd universal testing machine at a constant speed of 300 mm/min. The tests were repeated ten times for each of five branch diameter groups (5.36, 8.00, 9.21, 10.87, and 12.35 mm). Cutting force data were collected using NEXYGEN software. Covariance analysis was conducted with branch diameter included as a covariate, isolating the effect of pruner design on hand force. Mean comparisons were performed using the LSD test at a 1% significance level. The results showed that the Ergopro pruner required the lowest cutting force in most diameter groups, especially for medium and thick branches, whereas Bossini DS-709 consistently required the highest force across all sizes. The greatest relative increase in hand force was observed in the Bulmaks BMX-286 pruner with a 504% rise from the smallest to the largest branch diameter, while the smallest increase was found in Herly HM204 at 177.5%. These findings highlight the influence of pruner design features—such as blade type, thickness, and weight—on cutting efficiency and ergonomic performance, offering valuable insights for tool selection in orchard management.

ÖZET

Bu çalışma, fındık sürgünlerinin kesilmesi sırasında kullanılan on farklı budama makasının kesme kuvveti gereksinimleri ile tasarım özelliklerini karşılaştırmalı olarak değerlendirmek amacıyla yürütülmüştür. Bitki materyali olarak fındık sürgünleri kullanılmış, kesme testleri 300 mm/dak sabit hızda Lloyd marka evrensel test cihazı ile gerçekleştirilmiştir. Her biri beş farklı dal çapı grubuna (5,36; 8,00; 9,21; 10,87 ve 12,35 mm) ait olmak üzere onar tekrarlı testler yapılmıştır. Kesme kuvveti verileri NEXYGEN yazılımı kullanılarak kaydedilmiştir. Kovaryans analizi, dal çapı kovaryet olarak dahil edilerek, budama makası tasarımının el kuvveti üzerindeki etkisini izole etmek amacıyla uygulanmıştır. Ortalama karşılaştırmaları ise %1 anlamlılık düzeyinde LSD testi ile yapılmıştır. Sonuçlar, özellikle orta ve kalın dallarda, Ergopro model budama makasının çoğu çap grubunda en düşük kesme kuvveti gereksinimine sahip olduğunu; buna karşın Bossini DS-709 modelinin tüm çap gruplarında sürekli olarak en yüksek kuvvet gereksinimine sahip olduğunu göstermiştir. En yüksek oransal artış, Bulmaks BMX-286 modelinde %504'lük bir artışla görülürken, en düşük artış Herly HM204 modelinde %177,5 olarak tespit edilmiştir. Bulgular, bıçak tipi, kalınlığı ve ağırlığı gibi budama makası tasarım özelliklerinin kesme verimliliği ve ergonomik performans üzerindeki etkisini ortaya koymakta olup, bahçe yönetiminde alet seçiminde önemli bilgiler sunmaktadır.

INTRODUCTION

The required shear force to cut vegetative materials is associated with the material's physico-mechanical properties and the blade's structure. It required performing proper cutting operation changes depending on various factors *(Zhang et al., 2023; Wilczyński et al., 2023).*

The most important of these factors are; the material's shear stress, properties of the material, the structure and usage of the blade (*Song et al., 2022; Pekitkan et al., 2020)*. Failure to take into account some basic factors in the design of a pruning shear to perform cutting may result in the worker's musculoskeletal disorders of the upper limbs due to the physical effort required to cut branches and repetitive actions *(Zahid et al., 2022; Minaei et al., 2023).* Lakshmi and Kumari (2016) also highlighted in their research that manual

pruning can place considerable strain on the tendons, bones, and nerves in workers' hands, wrists, and elbows.

For this reason, some limit values for human health have been reported for manual repetitive work, such as pruning used in agricultural production and maintenance.

According to the EN-1005-3 standard, the force to be applied by the hand shouldn't be above 300 N and desirable values should be in the range of 150-200 N, if possible *(Selvi, 2023).*

There are many references to pruning and pruning shears in the literature, but they do not address hand force for repetitive actions or design effect on efficiency. There are many comparative studies in this area. Some of them are; Parish (1998), Romano et al. (2010), Marini et al. (2020), Ramanjineyulu et al. (2024), Sessiz et al. (2015), Selvi and Kabaş (2016).

From a design point of view, it will be seen that a classical pruning shear consists of the following main parts (Figure 1). In addition, some descriptive sizes of the pruning shears are shown in Figure 2.

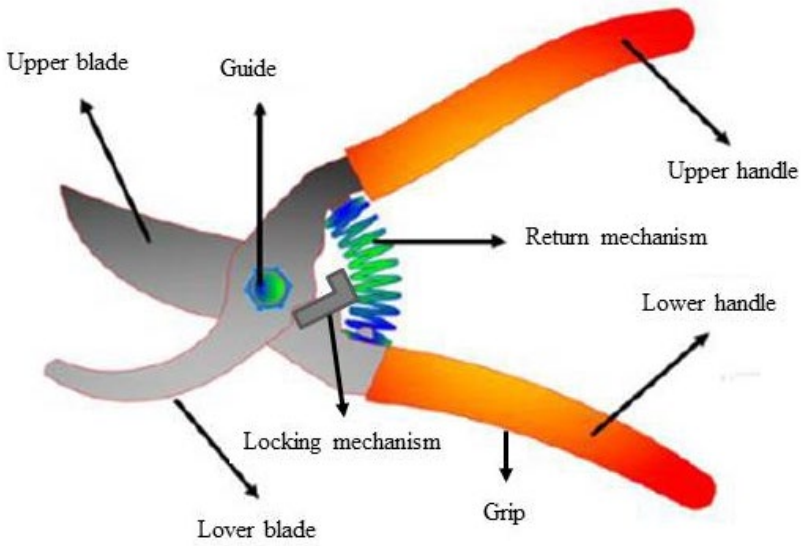


Fig. 1 - Main parts of pruning shear

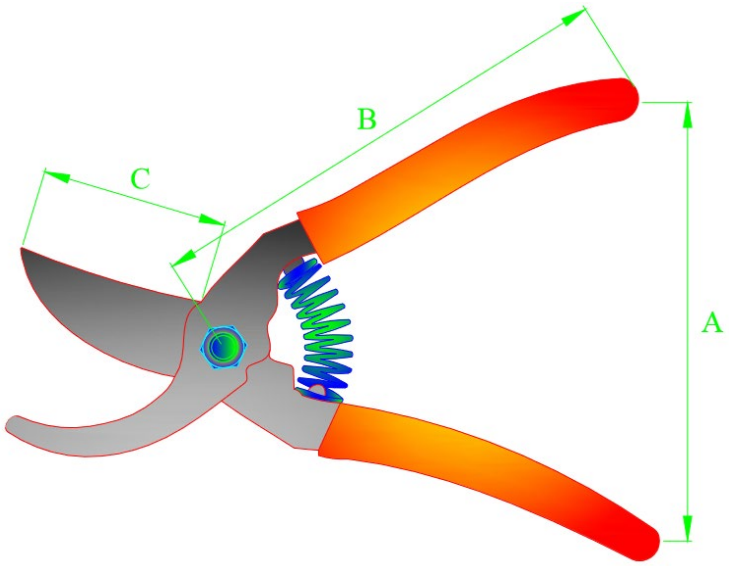


Fig. 2 - Some descriptive sizes of the pruning shears
A- Handle Spacing B- Handle Length C- Blade Length

In addition to this basic representation, it is also seen that pruning shears are examined in two groups: anvil (one blade cuts down against a flat surface) and bypass (two blades pass each other, like scissors). In the design of both types of pruning shears; different return mechanisms such as coil spring, leaf spring and telescopic spring can be used.

In addition, in a comprehensive study carried out by Paivinen (2000), besides the factors such as the locking mechanism, the force transfer mechanism, the guide, weight, stiffness, the returning mechanism is also specified as a design parameter.

The objective of this study was to compare low cost hand pruning shears, both types and returning mechanism, to determine which ones required the low hand force especially in terms of their design and also for hand health according repetitive works such as pruning.

MATERIALS AND METHODS

PLANT MATERIAL

In the shear tests, hazelnut suckers were obtained from a commercial hazelnut garden in Samsun province located in North of the Turkey from the pruning of the autumn period (October-November) between 2018 and 2019 (Figure 3).

The test samples were randomly cut by hand from vineyards. The cut and collected suckers were transported to the laboratory at the Department of Agricultural Machinery and Technologies Engineering, University of Ondokuz Mayıs which were then placed in a refrigerator at 5 °C until the time of the cutting tests.

The test procedure consisted of measuring the force on the handle required to cut hazelnut suckers of several diameters: 5.36, 8.00, 9.21, 10.87 and 12.35 mm.

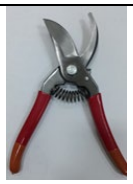
Fig. 3 - Hazelnuts suckers

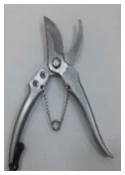
Pruning shears

Ten low cost hand pruning shears were selected for evaluation. The models are listed in table 1 and include an anvil and nine bypass pruners.

Table 1

Some information of pruning shears evaluated

Pruners	Figure	Type	Pruners sizes / mm	Blade thickness / mm	Weight / g	Retail Price
Yeniay		Bypass	A= 150 B= 150 C= 60	4.4	365	24.69
Unknown-1		Bypass	A= 127 B= 133 C= 50	2.1	147	34.67

Akman		Bypass	A= 123 B= 136 C= 52	3.7	187	31.10
Herly HM204		Bypass	A= 132 B= 130 C= 50	2.5	214	49.53
Ergopro		Anvil	A= 102 B= 146 C= 42	2.6	280	59.31
Bulmaks BMX-286		Bypass	A= 150 B= 156 C= 67	2.2	471	33.89
Unknown-2		Bypass	A= 120 B= 136 C= 57	2.95	167	17.90
Akman SNR		Bypass	A= 103 B= 142 C= 50	3.2	168	29.90
Bossini DS-308		Bypass	A=120 B=141 C= 59	5.2	268	20.00
Bossini DS-709		Bypass	A=158 B=146 C= 71	7.4	422	20.00

All of the pruning shears were purchased new for this evaluate. The plant materials were pre-experimented to simulate manual cutting, with a repetition of 300 mm / min at constant speed and 5 different diameter groups (5.36 mm, 8.00 mm, 9.21 mm, 10.87 mm and 12.35 mm) with 10 replications. This cutting velocity value was determined by a preliminary experiment with a pruning shears outside the trial, depending on the way taken during cutting.

Testing device and aparatus

The force required to cut hazelnut suckers with different pruning shears was measured by a Lloyd Instrument Universal Testing Machines (Lloyd Instrument LRX Plus, Lloyd Instruments Ltd, An AMATEK Company). The device has three main parts: moving head, driving unit and data acquisition system (load

cell, note book and connections and NEXYGEN Plus software). The device was equipment with a load cell of 1000 N and measurement accuracy of load cell was 0.5%. Load cell was fixed to moving head (Figure 4).

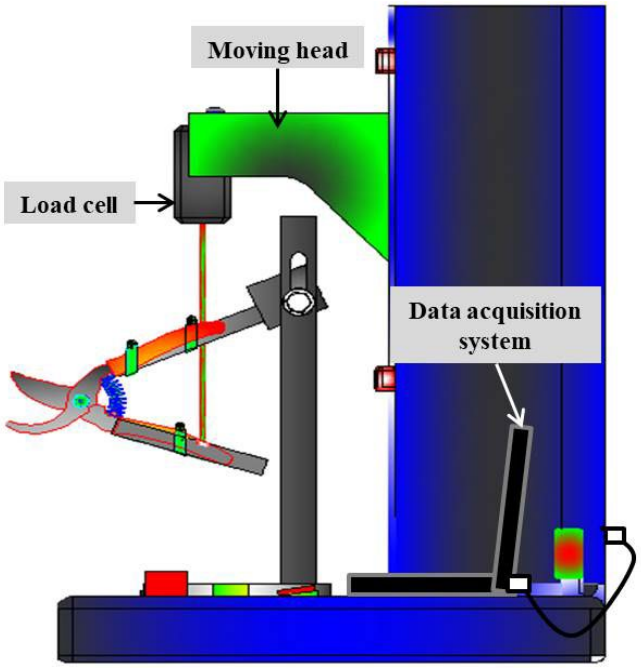


Fig. 4 - View of the universal testing machine used to measure the cutting force required for hazelnut sucker pruning

In the experiments, a clamping apparatus has been manufactured in order to enable the cutting shears to perform the correct cutting operation and to be mounted on the test device. The detail picture and dimensions of the clamping apparatus is shown in Figure 5. Pre-trials were performed to represent the cutting process with pruning shears and the cutting speed was chosen as 300 mm/min. The apparatus was guided vertically to assure that the force would be applied vertically with minimal lateral friction effects.

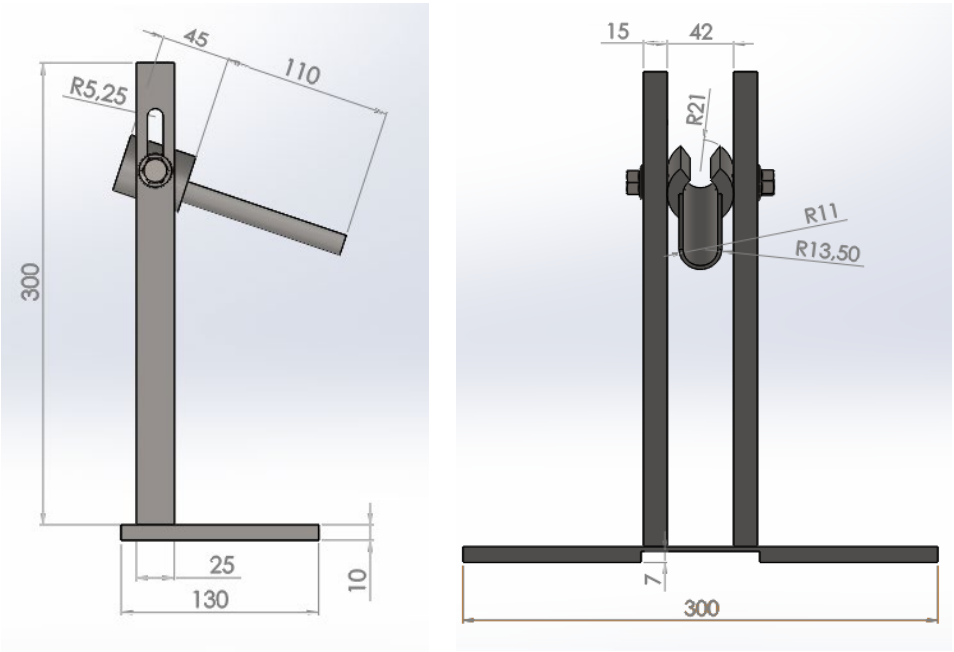


Fig. 5 - Clamping apparatus to the Lloyd LRX Plus tester

In statistical analyzes, moisture and diameter values of hazelnut suckers were included in the model as covariates and their effect was eliminated from the model and only the effect of ergonomic design effect

on force values was investigated. The LSD test was used for comparisons between means, while univariate analysis of variance was used for data analysis.

RESULTS AND DISCUSSION

The pruning shear type and design had a significant effect on the hand force required to cut hazelnut suckers across different branch diameters. Table 2 and Figure 6 presents the mean hand force (N) exerted by users to cut branches of varying diameters using ten different pruning shears.

The results reveal clear trends associated with blade type, handle design, weight, and blade sharpness.

Table 2

Mean hand force for pruning shears to cut hazelnut suckers (figures are the mean of cuts on 10 branches)

Model	Mean Hand Force, N				
	5.36 mm Branch	8.00 mm Branch	9.21 mm Branch	10.87 mm Branch	12.35 mm Branch
Akman	121 ^{bc}	250 ^{b}	333 ^{a}	334 ^{b}	357 ^{c}
Akman-SNR	92 ^{de}	203 ^{c}	222 ^{bc}	284 ^{c}	352 ^{c}
Bossini DS-308	111 ^{cd}	192 ^{cd}	236 ^{b}	363 ^{b}	438 ^{b}
Bossini DS-709	182 ^{a}	321 ^{a}	368 ^{a}	451 ^{a}	561 ^{a}
Bulmax BMX-286	50 ^{f}	144 ^{ef}	184 ^{c}	236 ^{de}	302 ^{d}
Ergopro	51 ^{f}	94 ^{g}	99 ^{d}	153 ^{g}	167 f
Herly	80 ^{e}	149 ^{def}	187 ^{c}	201 ^{ef}	222 ^{e}
Unknown-1	74 ^{e}	177 ^{cde}	209 ^{bc}	269 ^{cd}	323 ^{cd}
Unknown-2	140 ^{b}	216 ^{bc}	247 ^{b}	293 ^{c}	409 ^{b}
Yeni ay	50 ^{f}	124 ^{fg}	188 ^{c}	193 ^{f}	233 ^{e}

*Means in each column followed by the same letter are not significantly different at the 0.05 level

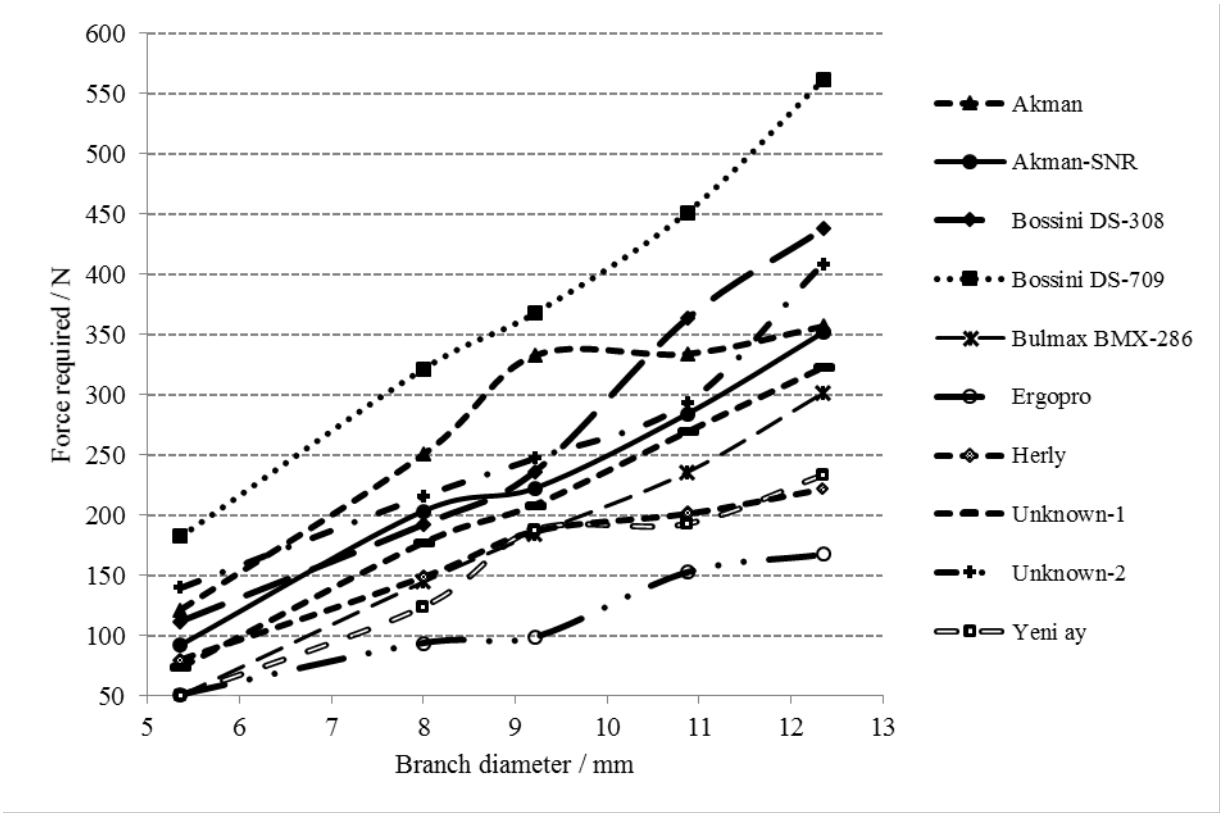


Fig. 6 - Force required to cut hazelnut suckers

For the smallest branch size (5.36 mm), the lowest mean hand force was observed with the Bulmax BMX-286, Ergopro, and Yeniay models (50–51 N), which were statistically similar ($p < 0.05$) and significantly lower than other models. In contrast, Bossini DS-709 required the highest force (182 N), suggesting that despite its larger dimensions and greater blade thickness (7.4 mm), its design does not facilitate ease of cutting in small-diameter branches.

This might be due to its heavier weight (422 g) and relatively wide blade, which could increase friction during initial cutting. As branch diameter increased to 8.00 mm and beyond, the trend in required hand force followed a similar pattern, though differences between models became more pronounced. At 8.00 mm, the Ergopro (94 N) and Yeniay (124 N) remained among the most efficient tools, while Bossini DS-709 and Akman required significantly higher forces (321 N and 250 N, respectively). The anvil-type Ergopro, despite its different cutting mechanism, consistently showed low force requirements, especially in thinner branches, indicating that its blade design and ergonomics were well-suited for ease of use.

For thicker branches (9.21–12.35 mm), the Bossini DS-709 consistently required the highest hand forces (368–561 N), which can be attributed to its high blade thickness (7.4 mm) and possibly suboptimal ergonomic design.

The excessive force requirement for this model may increase the risk of musculoskeletal strain during prolonged use, making it less suitable for large-scale orchard operations. Conversely, Bulmax BMX-286 continued to perform favorably with relatively low force values across all branch sizes (184 N to 302 N), suggesting that its combination of long blade length (C=67 mm) and lightweight design (471 g) contributes to a more efficient force transmission during cutting. However, the Ergopro showed a notable limitation in cutting thicker branches (≥10.87 mm), where the force requirement increased steeply to 153–167 N. While still low compared to some models, this sharp rise suggests that the anvil mechanism may be less effective on thicker woody branches due to the lack of a bypass action that reduces crushing.

A key observation is the consistent performance of Akman-SNR, which offered a good balance between cutting efficiency and ergonomic performance. It required moderate force levels across all diameters (92–352 N), significantly lower than the Akman model, despite their similar design and dimensions. This indicates that even minor design variations (e.g., blade sharpness, joint resistance, handle angle) can result in meaningful differences in user experience and efficiency.

Overall, bypass pruners generally required more force than the anvil-type Ergopro on smaller branches, though they performed better in thicker branch cutting due to their slicing action. Among bypass pruners, Bulmax BMX-286 and Yeniay demonstrated the most ergonomic performance. Weight and blade thickness also showed clear influence: heavier shears with thicker blades (e.g., Bossini DS-709) tended to require more hand force, likely due to increased resistance and less precise blade alignment.

These findings are critical for tool manufacturers and agricultural workers. Selecting pruners with appropriate weight, blade type, and ergonomic handle design can significantly reduce physical effort and fatigue, enhancing productivity and reducing the risk of repetitive strain injuries. For hazelnut sucker cutting, tools like Bulmax BMX-286, Yeniay, and Ergopro are recommended based on their lower required hand forces and ease of use across a range of branch diameters.

CONCLUSIONS

This study demonstrated that the design and structural properties of pruning shears significantly affect the hand force required during hazelnut sucker cutting. Among the evaluated models, the Ergopro pruner required the lowest cutting forces overall, particularly in medium and thick branch diameters, making it the most ergonomically favorable option. In contrast, the Bossini DS-709, characterized by its higher weight and blade thickness, consistently demanded the highest hand forces across all diameter groups, indicating lower efficiency and increased user fatigue risk.

Furthermore, the analysis of force variation across different branch sizes revealed that the Bulmaks BMX-286 had the greatest relative increase (504%), while the Herly HM204 showed the smallest (177.5%), emphasizing the impact of shear design on adaptability to branch thickness. The bypass-type pruners generally performed better than expected in small diameters, but their performance varied significantly based on weight, blade thickness, and handle dimensions.

The findings of this research provide practical insights for tool manufacturers and orchard workers by identifying key design features that influence cutting performance. Selecting ergonomically designed pruners can reduce musculoskeletal strain, improve productivity, and enhance user comfort during repetitive

agricultural tasks. Future studies may expand this work by including muscle activity analysis (EMG), operator fatigue assessment, or long-term field trials to further validate laboratory-based findings

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APPLICATION OF UAV MULTISPECTRAL IMAGERY FOR VINEYARD MANAGEMENT THROUGH VEGETATION STATUS ASSESSMENT

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APLICAREA IMAGINILOR UAV MULTISPECTRALE PENTRU MANAGEMENTUL VITICOL PRIN EVALUAREA STĂRII DE VEGETAȚIE

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Keywords: *vineyard, UAV, NDVI, multispectral imagery, precision viticulture*

ABSTRACT

This paper presents a methodology for assessing vineyard vegetative condition using vegetation indices derived from high-resolution unmanned aerial vehicle (UAV) multispectral imagery. Aerial monitoring campaigns were conducted using agricultural UAV equipped with MAPIR Survey 3 multispectral camera. Flight paths and navigation waypoints were planned in Mission Planner software to ensure uniform ground sampling distance and adequate image overlap. Acquired imagery was processed in Agisoft to produce georeferenced orthomosaics, dense point clouds, and digital elevation models (DEMs). The normalized difference vegetation index (NDVI) was subsequently calculated to map intra-plot variability in vine vigor. NDVI maps revealed spatial heterogeneity at the row level, enabling the delineation of management zones and early identification of low-vigor areas. This approach supports the implementation of precision viticulture strategies by providing detailed canopy condition information, reducing field labor and allowing optimized input management.

REZUMAT

Lucrarea prezintă o metodologie pentru evaluarea stării vegetative a viței de vie utilizând indici de vegetație derivați din imagini multispectrale de înaltă rezoluție achiziționate prin intermediul unui vehicul aerien fără pilot (UAV), echipat cu camere multispectrale MAPIR Survey 3. Traseele de zbor și punctele de navigație au fost planificate în software-ul Mission Planner pentru a asigura o distanță uniformă de eșantionare la sol și o suprapunere adecvată a imaginilor. Imaginile achiziționate au fost prelucrate în Agisoft pentru a obține ortofotoplanuri georeferențiate, nori de puncte denși și modele digitale de elevație (DEM). Ulterior, a fost calculat indicele diferențial normalizat de vegetație (NDVI) pentru a cartografia variabilitatea intraparcelară a vigorii butucilor. Hărțile NDVI au evidențiat heterogenitatea spațială la nivel de rând, permițând delimitarea zonelor de management și identificarea timpurie a zonelor cu vigurozitate scăzută. Această abordare sprijină implementarea strategiilor de viticultură de precizie prin furnizarea de informații detaliate despre starea coronamentului, reducerea muncii pe teren și optimizarea aplicării inputurilor.

INTRODUCTION

Precision viticulture (PV) is a site-specific management approach aimed at optimizing grape quality and yield by monitoring spatial and temporal variability in vineyard conditions. Recent advances in remote sensing technologies have significantly improved the ability to characterize canopy vigor and variability at multiple scales (*Matese et al., 2015; Sassu et al., 2021).*

Satellite platforms such as Sentinel-2 have been widely used in viticulture because of their temporal frequency and multispectral capabilities. However, their spatial resolution (10–20 m) is often insufficient for discriminating individual vine rows, especially in narrow-spacing vineyards (*Di Gennaro et al., 2019; Campos et al., 2021*). UAV (Unmanned Aerial Vehicle) platforms equipped with multispectral cameras overcome this limitation by providing centimeter-level resolution, which allows detailed assessment of vine vigor, canopy structure, and missing plants (*Pádua et al., 2018; Vélez et al., 2023; Gavrilović et al., 2024*).

The normalized difference vegetation index (NDVI) is among the most widely used vegetation indices in viticulture for evaluating canopy density, leaf area index (LAI), and chlorophyll content (*Rouse et al., 1974; Campos et al., 2021; Reynolds et al., 2018*). NDVI-derived vigor maps facilitate the delineation of

management zones and the detection of low-vigor or stressed plants, enabling variable-rate application of fertilizers and crop protection products (*Primicerio et al., 2012; Kandylakis et al., 2020; Serrano et al., 2023*).

UAV-based multispectral sensing also supports the estimation of canopy geometric parameters such as canopy height, tree row volume (TRV), and leaf wall area (LWA), which are critical for optimizing pesticide dose and irrigation scheduling (*Poblete-Echeverría et al., 2017; Campos et al., 2021; Mesas-Carrascosa et al., 2019; Gavrilović et al., 2024*). Moreover, UAV-derived data have been successfully employed for water stress estimation (*Kandylakis et al., 2020*), multi-temporal vigor mapping (*Pádua et al., 2019*), and detection of Botrytis cinerea incidence (*Vélez et al., 2023*).

Recent studies underscore the operational benefits of UAV-based NDVI maps in precision viticulture, demonstrating their role in reducing field scouting requirements, improving the accuracy of vineyard management decisions, and enabling cost-effective site-specific strategies (*Comba et al., 2019; Poblete-Echeverría et al., 2017; Sassu et al., 2021; Reynolds et al., 2018*).

The aim of this study is to present a robust UAV-based methodology for determining vineyard vegetative condition by producing NDVI maps at centimeter-level resolution. This approach enables accurate detection of intra-plot canopy variability and supports the implementation of site-specific management strategies without relying on external satellite data sources.

MATERIALS AND METHODS

The initial phase in generating spectral maps of the vineyard crop through the aerial monitoring system based on an agricultural drone involved the precise planning and autonomous execution of the UAV flight over the targeted vineyard area. This step was implemented using the Mission Planner software, a ground control station application that allows for the configuration of flight parameters, georeferenced mission planning, and onboard navigation automation.

Within Mission Planner, the flight route was defined by inputting a set of waypoints that ensured full coverage of the vineyard parcel with adequate image overlap. Specific flight parameters included:

- Altitude: set between 40–60 meters AGL (Above Ground Level);
- Forward and side overlap: maintained above 80% to ensure sufficient stereoscopic coverage for photogrammetric processing;
- Flight speed and camera trigger interval: calibrated to match the resolution of the MAPIR Survey 3 multispectral sensor.

The mission planning accounted for environmental conditions (e.g., solar angle, wind) and GNSS signal quality to ensure accurate geotagging of the captured imagery. Upon take-off, the drone autonomously followed the programmed flight path in “AUTO” mode, navigating to the designated waypoints and triggering the camera at predefined intervals to acquire high-resolution multispectral data of the vine canopy. Once the mission was completed, the UAV automatically returned to the predefined “HOME” location for landing.

Fig. 1 - UAV agricultural monitoring platform

To generate the spectral maps using the aerial spectral monitoring system based on an agricultural drone, the following steps were carried out:

- real-time UAV flight monitoring;

Fig. 2 - Mission Planner "FLIGHT DATA" interface showing real-time UAV flight monitoring.

- flight path planning;

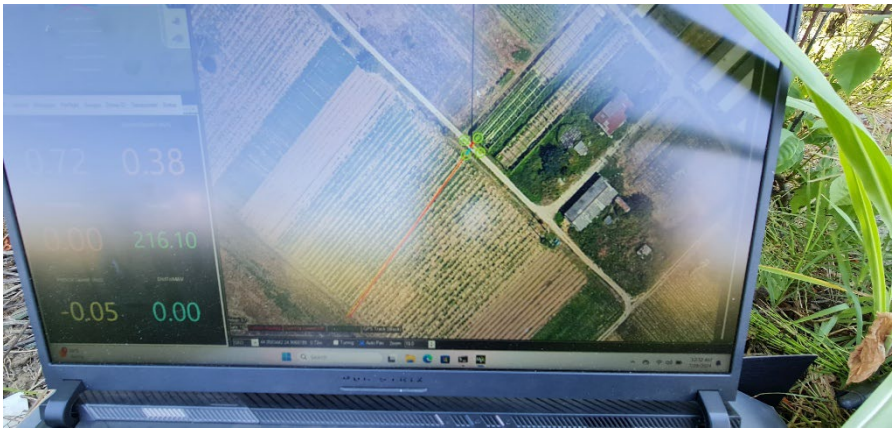

Fig. 3 - Flight path planning

- defining the flight path

Fig. 4 - Flight path planning using polygonal waypoint definition

- start of the agricultural drone flight ("LOITER" mode);

Fig. 5 - UAV take-off phase in "LOITER" mode

- after the drone take-off, the flight switched to "AUTO" mode;

Fig. 6 - UAV take-off

- the drone headed toward the intermediate waypoints, after which it began the actual mission of monitoring the vineyard crop;

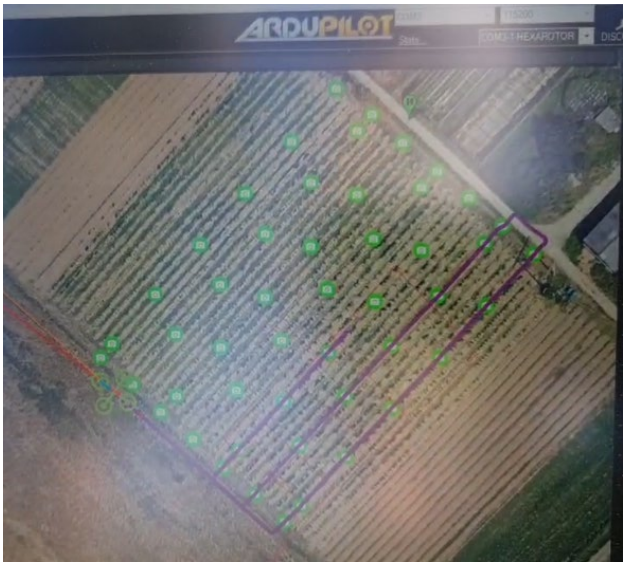

Fig. 7 - Transition to "AUTO" flight mode for mission execution.

- completion of the monitoring mission and return of the drone to the take-off/landing point "HOME".

Following the flight over the monitored vineyard crop, the images obtained using the MAPIR Survey 3 agricultural multispectral camera with integrated GPS were processed using the Agisoft Photoscan photogrammetry software by following these steps:

- the files captured by the MAPIR Survey 3 agricultural multispectral camera with integrated GPS were copied;
- the Agisoft software was launched;
- the photographs captured by the MAPIR Survey 3 multispectral camera were imported into Agisoft;

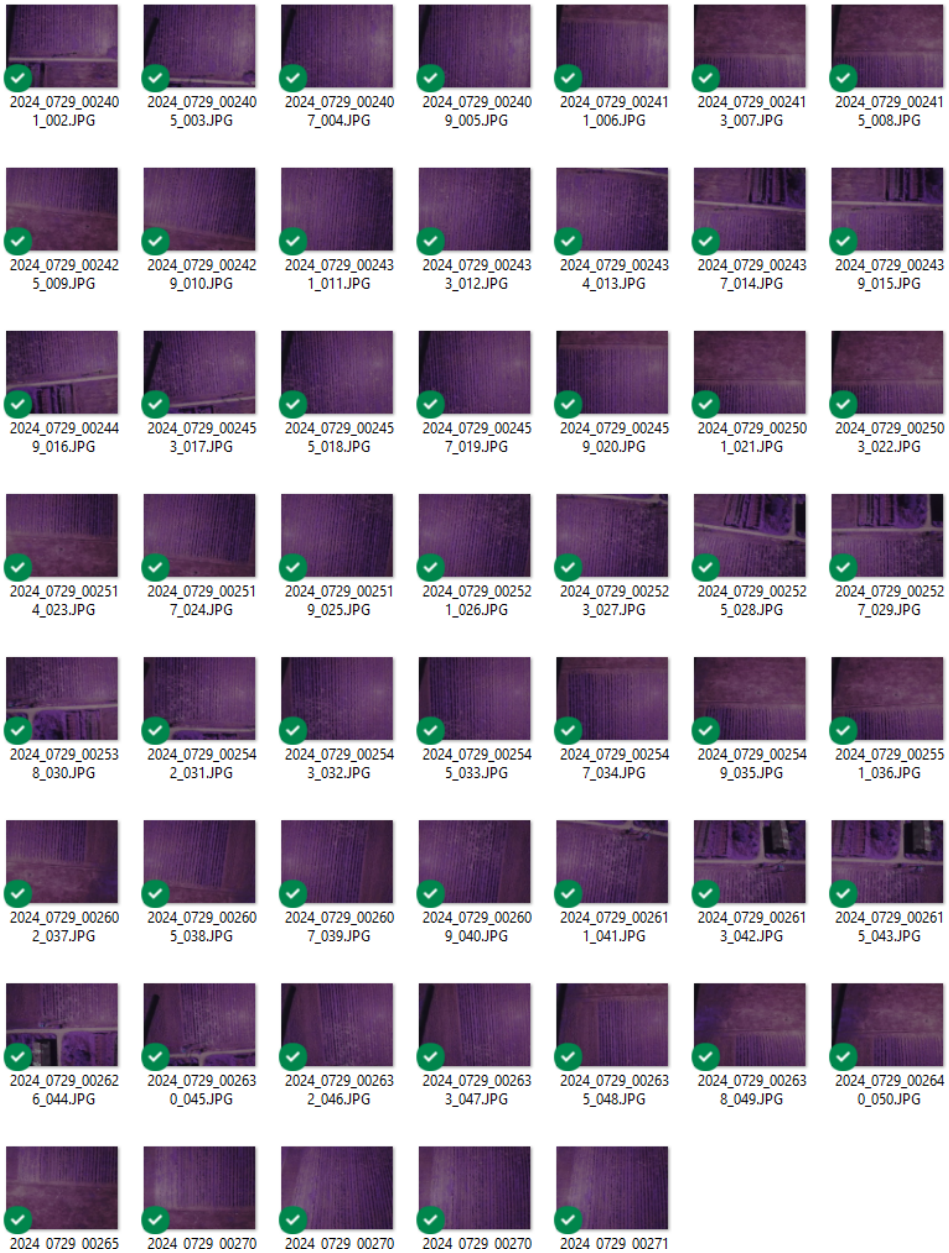

Fig. 8 - Photographs taken with the multispectral camera

- unsuitable images were removed;
- from the “Photos - Change View” menu, the images were displayed in detail;
- the image quality was checked using the “Estimate Image Quality – All Cameras” menu;
- the “Show Cameras” menu was used to display the image acquisition layout and their location;
- proper alignment of the image locations and the horizon was performed via the “Workflow – Align Photos – High” option (“Reference preselection” was enabled as GPS information was available in the photographs);
- the image alignment and the UAV flight path were obtained;
- the three-dimensional dense cloud (Dense Cloud – containing more details) was displayed and transformed into a 3D model;
- the “Workflow – Build Mesh” menu was accessed;

- the “Workflow – DEM” menu was accessed;

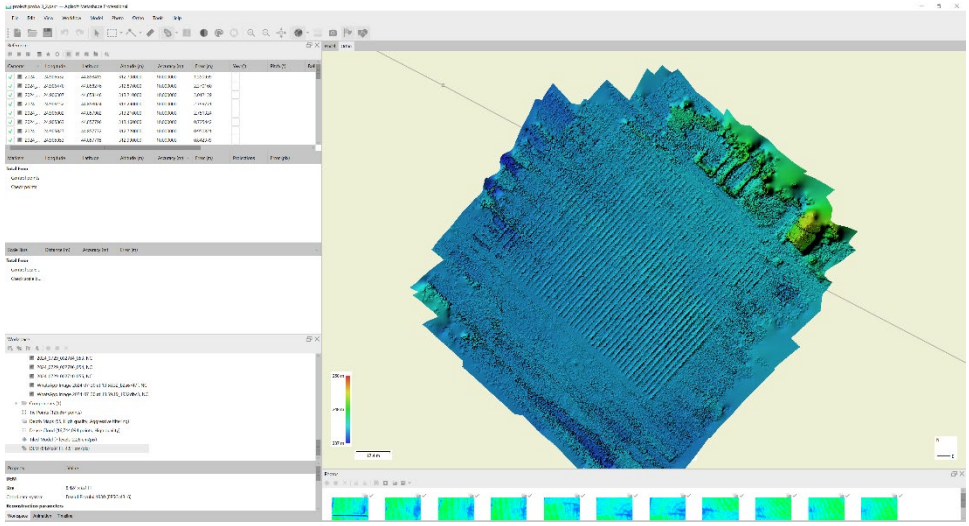

Fig. 9 - Digital Elevation Model (DEM) image

- the “Workflow – Build Orthomosaic” menu was accessed and data were processed;

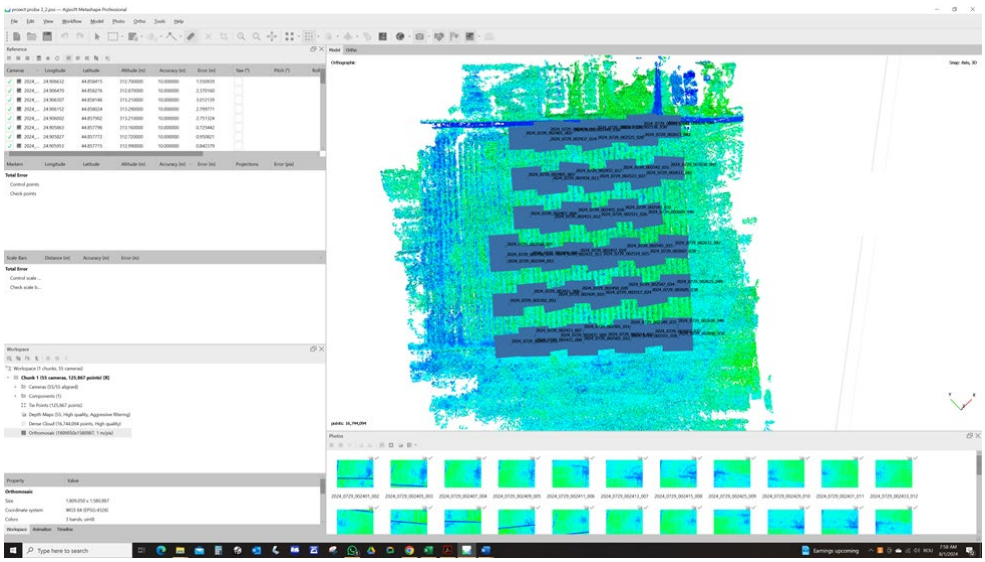

Fig. 10 - Orthomosaic image showing the identified images positioned according to GPS coordinates

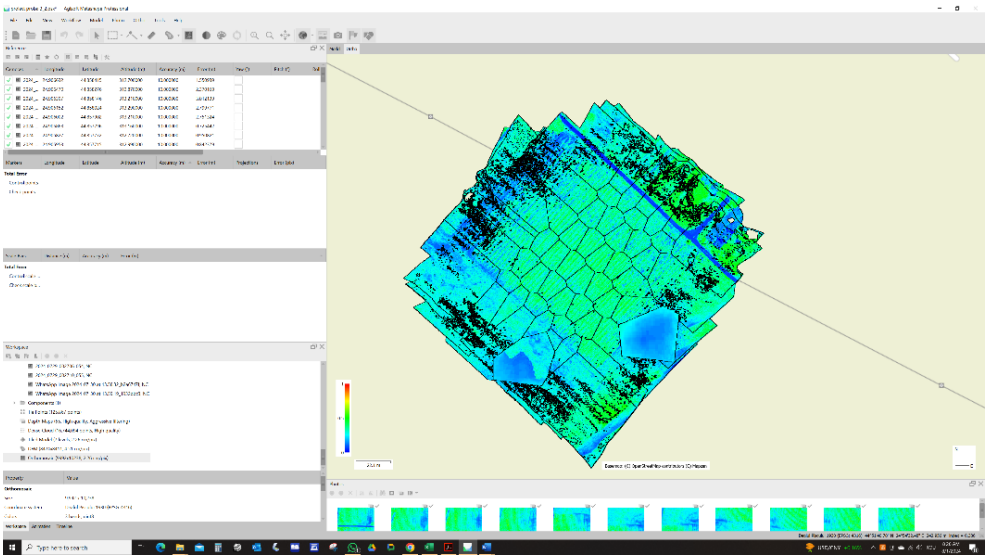

Fig. 11 - Orthomosaic image showing the alignment of processed photographs

- the orthomosaic was exported and saved in tiff format;

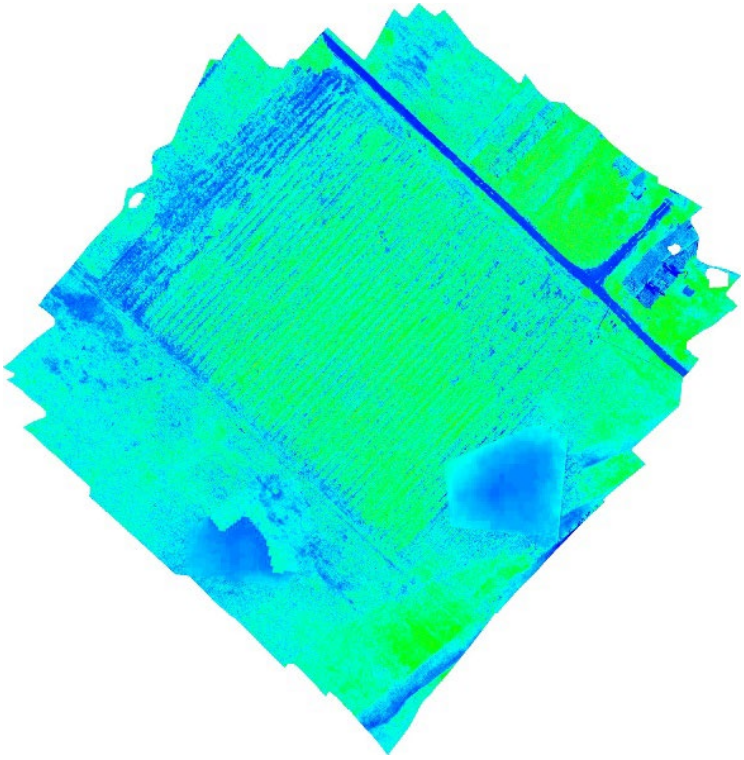

Fig. 12 - Orthomosaic image saved in JPEG format using the software

- the NDVI (Normalized Difference Vegetation Index) map was obtained, which is a non-linear transformation of the visible (RED) and near-infrared (NIR) bands defined as the difference between these two bands divided by their sum – using the "Tools – Set Raster Transform" menu.

The NDVI (Normalized Difference Vegetation Index) is a widely used indicator in remote sensing and environmental monitoring. It measures vegetation amount and health based on data derived from satellite images or ground-based sensors. NDVI is calculated using information from two different spectral bands, typically a red (RED) band and a near-infrared (NIR) band. The NDVI formula is as follows:

$$NDVI = \frac{NIR-RED}{NIR+RED}, \quad [-] \qquad (1)$$

where:

NIR - represent reflectance values in the near-infrared, [-];
RED - represent reflectance values in the red bands, [-].
The resulting value ranges from -1 to +1. Interpretation of NDVI values is as follows:

- Negative values (close to -1): Indicate surfaces covered by water or other non-vegetated areas such as snow, rock, or buildings. Negative NDVI suggests an absence of vegetation or very sparse vegetation;
- Low values (close to 0): Indicate very little vegetation, arid agricultural land, or regions with stressed or diseased vegetation;
- High values (close to +1): Indicate healthy and abundant vegetation. The closer NDVI is to +1 (>0.6), the healthier and denser the vegetation.

RESULTS

The use of NDVI in table grape crops can provide valuable information about vine health and overall condition and can be applied at various stages of crop management, such as:

- monitoring vine growth throughout the growing season;
- detecting vegetative stress: NDVI values lower than expected may indicate stress in the crop caused by water deficits, nutrient deficiencies, diseases, or pests. Early detection allows timely interventions to improve plant health;

- irrigation planning: NDVI can be used to determine irrigation needs based on the current vegetation status. Low NDVI values may indicate the need for additional water to avoid drought stress;
- assessing grape ripeness: prior to harvest, NDVI can be used to evaluate grape ripeness. Specific NDVI values can indicate the optimal harvest time, helping to ensure superior grape quality;
- identifying plant health issues: NDVI values can reveal areas with plant health problems, such as disease infections or pest infestations;
- production monitoring: collecting NDVI data over time can help estimate production potential and assess yields in table grape crops.

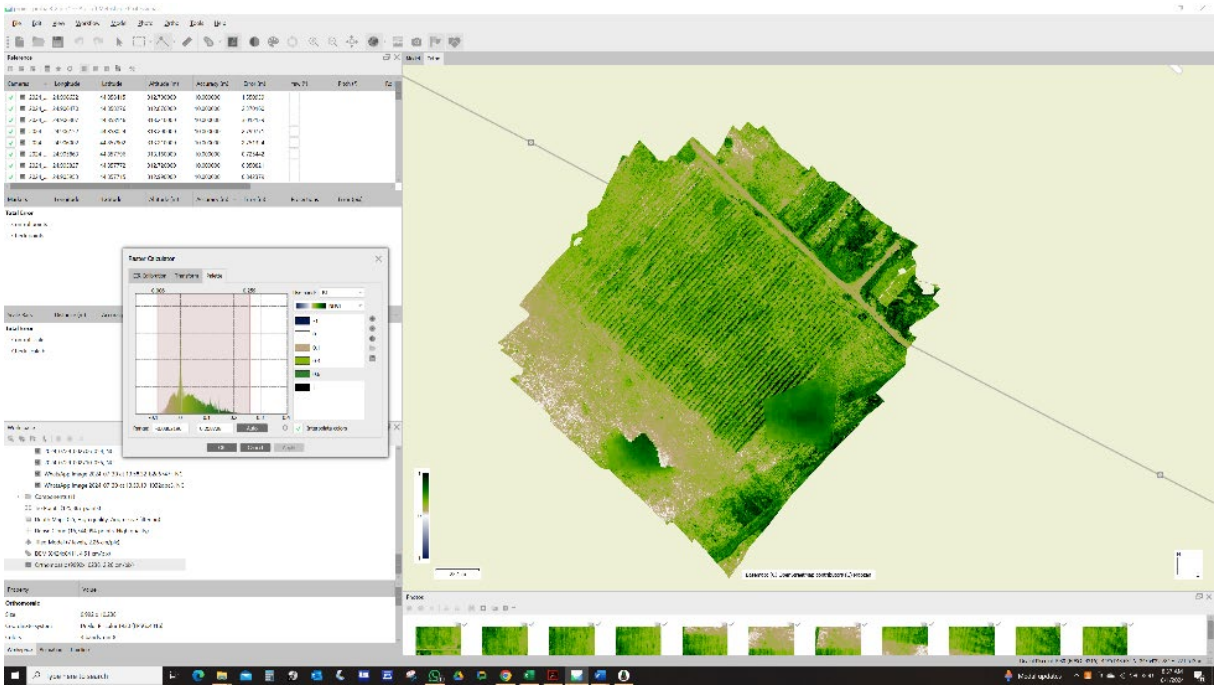

Fig. 13 - NDVI map of the monitored area

Color interpretation:

- Green areas: High NDVI values indicating healthy, dense vegetation. The darker the green, the healthier and denser the vegetation;
- Light green to yellow areas: Moderate NDVI values indicating less dense or stressed vegetation;
- White or very bright areas: Low NDVI values indicating bare soil, built-up areas, or non-vegetated surfaces.

Histogram and statistics:

- The histogram shows the distribution of NDVI values in the mapped area;
- A peak at higher NDVI values (closer to +1) indicates that most of the area is covered with healthy vegetation;
- A significant portion of the histogram at lower values (closer to 0 or negative) indicates non-vegetated areas or stressed vegetation.
- Parcel analysis:
- The studied parcel is predominantly green, suggesting that most of the area is covered with vegetation (healthy vine rows and inter-row vegetation);
- Some lighter green or yellow areas may indicate lower vegetation density or stressed plants, which could be due to factors such as soil quality, water availability, or crop health;
- White patches may correspond to roads, paths, or bare soil within the field.

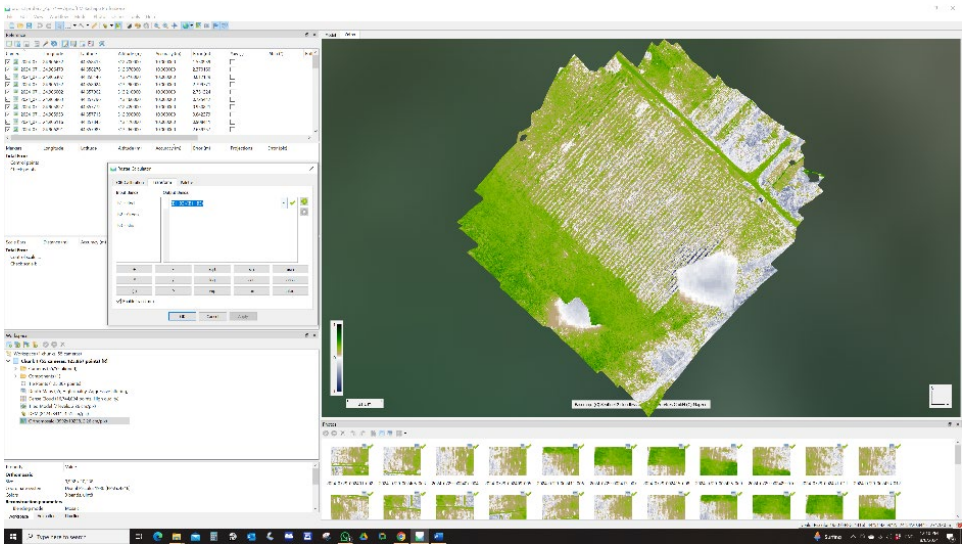

Fig. 14 - Red–Blue / (Red + Blue) map of the monitored area

The formula (Red - Blue) / (Red + Blue) is a type of vegetation index that emphasizes the difference between the red and blue spectral bands normalized by their sum. This specific index can provide information about vegetation characteristics, although it is less commonly used compared to indices such as NDVI.

Index interpretation:

- Numerator (Red - Blue):
  - The red band is typically absorbed by chlorophyll in healthy vegetation, leading to lower reflectance values in this spectral region;
  - The blue band is also absorbed by chlorophyll but generally less than the red band, depending on vegetation health and type;
  - The difference between red and blue can help highlight areas where vegetation absorbs these wavelengths differently.
- Denominator (Red + Blue):
  - Normalizes the difference, accounting for variations in lighting conditions or surface reflectance that could affect overall reflectance intensity.
  - Vegetation characteristics:
  - High index values: Indicate a greater difference between red and blue bands, suggesting strong absorption in the red band (due to high chlorophyll content) and relatively lower absorption in the blue band. These areas likely correspond to healthy vegetation;
  - Low index values: Occur when the difference between red and blue bands is small, suggesting either low absorption in both bands (possibly due to stressed vegetation, bare soil, or non-vegetated surfaces) or similar reflectance in both bands. This could also indicate water bodies, as water typically reflects both red and blue light.

Applications and limitations: This index can help differentiate vegetated from non-vegetated surfaces and may be useful in detecting vegetation stress, soil exposure, or water presence. However, it may not be as sensitive or specific as other vegetation indices, such as NDVI, which specifically use the near-infrared band in combination with the red band to highlight vegetation vigor and biomass.

CONCLUSIONS

Satellite- and UAV-based remote sensing, through the use of multispectral measurements, has significant applications in viticulture as in precision agriculture. These technologies enable detailed assessment of vine health and soil conditions, which are essential for quality wine production. Soil reflectance spectra can provide information about moisture content and organic matter, which are crucial for effective irrigation and fertilization management.

Identifying specific soil constituents, such as clay minerals and iron oxides, helps viticulturists better understand soil fertility and its influence on grape characteristics. Narrow-band or hyperspectral imagery,

together with advanced analytical techniques, can facilitate monitoring vine conditions and early detection of water stress or diseases.

However, current spaceborne instruments have limitations in resolution and spectral bands. This highlights the need to improve remote sensing technologies to support modern viticulture, thereby enhancing wine quality and optimizing cultivation practices

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ASPECTS REGARDING THE REMEDIATION OF SOILS POLLUTED WITH POLYCYCLIC AROMATIC HYDROCARBONS THROUGH OZONATION
/
ASPECTE PRIVIND REMEDIEREA SOLURILOR POLUATE CU HIDROCARBURI AROMATICE POLICICLICE PRIN OZONARE

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ABSTRACT

This study investigates the effectiveness of ozone treatment, with and without toluene, for the remediation of soils contaminated with polycyclic aromatic hydrocarbons (PAHs). The results highlight complex mechanisms of both direct and indirect oxidation, influenced by the contaminant composition and the organic matter content of the soil. Ozonation in the presence of toluene enhanced contaminant mobilization through desorption and the formation of surfactant-like intermediates, facilitating oxidation. After 18 hours of treatment, a significant reduction in hydrocarbon was observed, particularly for highly unsaturated PAHs. Moreover, ozone proved effective not only in degrading easily oxidizable fractions but also resistant hydrocarbon biomarkers, indicating the potential of this technology for treating persistent residual hydrocarbons. The combined ozone–biodegradation treatment demonstrated higher efficiency in removing PAHs, including recalcitrant compounds, compared to individual methods, offering a promising solution for bioremediation of soils contaminated with complex pollutant mixtures. It was also noted that ozonation can generate poorly soluble intermediate products, such as asphaltenes, resulting from partial degradation of other fractions. Therefore, careful process management is essential to maximize treatment efficacy.

REZUMAT

Prezenta lucrare investighează eficiența tratamentului cu ozon, cu și fără adăugarea toluenului, în remedierea solurilor contaminate cu hidrocarburi policiclice aromatice (PAH). Rezultatele au evidențiat mecanisme complexe de oxidare directă și indirectă, influențate de compoziția contaminanților și conținutul de materie organică din sol. Ozonarea, în prezența toluenului, a condus la o mobilizare crescută a contaminanților prin desorbție și formarea unor produse intermediare surfactante, facilitând astfel oxidarea. După 18 ore de tratament, s-a înregistrat o reducere semnificativă a speciilor hidrocarburice, în special a PAH-urilor cu grad ridicat de nesaturare. În plus, ozonul s-a dovedit eficient nu doar în degradarea fracțiilor ușor oxidabile, ci și a unor biomarkeri hidrocaburi rezistenți, ceea ce indică potențialul acestei tehnologii în tratarea hidrocarburilor reziduale persistente. Tratamentul combinat ozonare – biodegradare s-a dovedit a fi mai eficient în eliminarea PAH-urilor, inclusiv a celor greu degradabile, comparativ cu metodele individuale, oferind o soluție promițătoare pentru bioremedierea solurilor contaminate cu amestecuri complexe de poluanți. Totodată, s-a observat că ozonarea poate genera produse intermediare greu solubile, cum ar fi asfaltenele, rezultate din degradarea parțială a altor fracții. Astfel, o gestionare atentă a procesului este esențială pentru maximizarea eficienței tratamentului.

INTRODUCTION

The contamination of sediments with polycyclic aromatic hydrocarbons (PAHs) represents a major environmental issue, given the toxicity, persistence, and bioaccumulation potential of these compounds. In this context, the development of effective remediation methods is essential. In the study conducted by Yu Zeng and P.K. Andrew Hong, the authors investigated the application of slurry-phase ozonation as a treatment technique for a PAH-contaminated sediment originating from a boat launch area polluted with coal tar. The results showed that a 2-hour ozonation led to a significant reduction (50–100%) in PAHs, while also

improving their bioavailability and biodegradability. Furthermore, the authors demonstrated the feasibility of an integrated chemical-biological approach, in which ozonation serves as a pretreatment for subsequent biological processes *(Zeng, Y., and Andrew Hong, P.K. 2011)*.

Another study highlighted that organochlorine pesticides mainly originate from pesticide use in ongoing agricultural activities, while PAH pollution stems from industrial sources (such as fossil fuel combustion, transportation, and technological processes), as well as from food packaging, processing, and transportation. The spatial distribution of these pollutants was significantly influenced by geo-climatic factors, such as precipitation, and by the physicochemical characteristics of the soil (including organic matter content and soil texture). Although the individual and cumulative carcinogenic risks of these compounds were below the critical threshold of 10^{-4}, children were found to be at higher risk compared to adults, indicating increased vulnerability within this population group. (*Liu, Y. et al, 2025)*.

A significant influence of soil properties—such as pH and clay content—on the behavior of PAHs has been observed. With the acceleration of urbanization and industrial development, intense anthropogenic activities over the past decades have led to a substantial increase in environmental contamination with hazardous organic pollutants. Among these, polycyclic aromatic hydrocarbons (PAHs) stand out due to their persistence, toxicity, mutagenic and carcinogenic potential, being considered a major threat to both the environment and human health (*Rusanescu, C.O. et al., 2023*). PAHs are frequently detected in various environmental media—air, water, soil—as well as in food products. In particular, the accumulation of PAHs in soil has a profound impact on terrestrial organisms, negatively affecting the growth, reproduction, and survival of plants, invertebrates, microorganisms, and even vertebrates. These toxic effects occur through two main exposure pathways: direct contact with contaminated soil and trophic transfer through the food chain. Moreover, due to their bioaccumulative capacity, PAHs can cause ecological imbalances and the loss of essential ecosystem functions (*Rusanescu, C.O. et al, 2024*).

Many developed countries have established ecological thresholds for PAHs in soil, taking into account both human health and ecological risks. Existing regulations primarily focus on protecting human health, while international ecological standards—such as Eco-SSL (USA, Ecological Soil Screening Levels), SQGE (Canada, Environmental and Human Health Soil Quality Guidelines), EILs (Australia, Investigation Levels for Soil and Groundwater), Eco-SGVs (New Zealand, Development of Soil Guideline Values for the Protection of Ecological Receptors), and ERL (Netherlands, Environmental Risk Limits)—integrate both direct exposure and trophic transfer through the food chain (*Han, G. et al. 2025).*

Given the toxic potential of these pollutants, this paper presents ozonation techniques as effective methods for treating environmental contaminants. Despite advances in pollution management, heteroatom-substituted polyaromatic compounds (PAXHs, where X = N, S, or O) remain toxic, often overlooked, yet widely distributed contaminants. Due to their stable structures, these compounds strongly adsorb to soil, significantly hindering remediation processes. Biodegradation has been successfully used for remediating soils contaminated with low-molecular-weight PAHs. However, bioremediation strategies have limited applicability in soils and aquifers contaminated with mixtures of high-molecular-weight PAHs. This limitation arises from the strong adsorption of these compounds to soil organic matter, the high structural stability resulting from resonance energy, and their low water solubility.

Ozone is a very powerful oxidizing agent (redox potential E_0 = +2.07 V) and has been successfully used in wastewater treatment for the oxidation of organic contaminants. It can oxidize organic compounds either directly or through the generation of hydroxyl radicals—or through both mechanisms. Following ozonation treatment, organic compounds are transformed into oxygenated intermediates, which are more water-soluble and more readily biodegradable *(Nam, K. and Kukor, J. 2000).*

MATERIALS AND METHODS

This paper synthesizes key aspects related to the remediation of soils contaminated with polycyclic aromatic hydrocarbons (PAHs) through ozonation. For this purpose, various specialized databases from recent years were consulted.

In the study conducted by Satilmis and Schrader (2023), toluene (≥99.8%) and ultrapure water were used for the ozonation process. The contaminated soil sample was collected from an industrial site, air-dried, homogenized, and sieved to 2 mm. In 25 mL vials, 85 mg of soil, 8 mL of toluene, and 10 mL of water were added. Ozone was continuously bubbled at room temperature for either 6 or 18 hours using a BMT 803N generator (1 L/h). Excess ozone was neutralized with manganese dioxide (MnO_2). After ozonation, the soil samples were filtered, dried, and subjected to Soxhlet extraction for 24 hours using 50 mL of

dichloromethane. The solvent was removed under reduced pressure, and the resulting residues were preserved for analysis. The liquid phases (water and toluene) were separated by liquid-liquid extraction. The organic phase was dried over magnesium sulfate, filtered, concentrated, and stored for further characterization *(Satilmis, I. and Schrader, W., 2023).*

RESULTS

It was found that direct ozonation of the contaminated soil, without the use of an organic solvent, did not lead to a significant removal of pollutants—most likely due to the strong binding of PAHs to the soil matrix. To increase contaminant accessibility, toluene was added as a solvent, which significantly improved ozonation efficiency. High-resolution mass spectrometry (APPI-UHRMS) enabled detailed characterization of the initial contaminants and the resulting oxidation products, revealing clear differences between the control sample and the solvent-assisted ozonated samples (with toluene), aimed at facilitating reactions between ozone and soil-adsorbed contaminants (at both 6 h and 18 h exposure times).

Following ozonation in the presence of toluene, new oxygenated species were detected, while signals corresponding to heavy PAHs and nitrogen-containing compounds decreased or were completely eliminated. For instance, the compound $C_{28}H_{17}N$ was almost entirely removed after 18 hours. Oxygenated compounds such as $C_{21}H_{18}O_6$, $C_{25}H_{18}O_3$, and $C_{22}H_{22}O_5$ were identified in increased concentrations.

The results indicated continued degradation of oxidized compounds and the formation of a wide range of oxidation products, highlighting the potential of ozonation as an effective method for remediating soils contaminated with PAXHs (*Satilmis, I. and Schrader, W., 2023*).

The distribution of compounds by heteroatom class showed the presence of various species in all three analyzed phases (organic, aqueous, and soil extract), confirming the transformation of PAHs into more polar oxidation products *(Satilmis, I. and Schrader, W. 2023).*

Analysis of the control sample showed that hydrocarbons (HC class) were the most abundant compounds, followed by nitrogen-containing species (NO, NO_2, N_2). Compared to the control, ozonation—particularly with the addition of toluene for 18 hours—led to a significant decrease in the number of hydrocarbons (from 3,211 to 2,183 species) and nitrogen-containing aromatic compounds (PANHs—from 2,052 to 522 species). However, after 6 hours of ozonation, a temporary increase in hydrocarbons was observed, likely due to more efficient extraction facilitated by toluene.

Ozonation generated a wide range of oxygenated compounds (up to O_{13}), but their number decreased after 18 hours, indicating the gradual degradation of intermediate products. The longer reaction time allowed for the transformation of high-molecular-weight compounds into smaller species *(Satilmis, I. and Schrader, W. 2023).*

After 6 hours of ozonation in the presence of toluene, hydrocarbons with up to 95 carbon atoms were detected in the organic phase (toluene), indicating the extraction of strongly adsorbed PAHs from the soil. In the aqueous phase, only a few hydrocarbon species were detected after both 6 and 18 hours of reaction. After 18 hours of ozonation, highly aromatic PAHs were completely eliminated from the soil. High-molecular-weight (HMW) PAHs appeared to degrade faster than low-molecular-weight (LMW) PAHs, possibly due to their lower concentrations in the soil (*Satilmis, I. and Schrader, W., 2023*).

The efficiency of toluene-assisted ozonation for treating soils contaminated with substituted polycyclic aromatic compounds (PAXHs) was demonstrated. In the absence of an organic solvent, direct ozonation did not result in significant contaminant reduction, suggesting strong adsorption in the soil matrix and limited accessibility for oxidation reactions. The addition of toluene increased contaminant mobilization through desorption and the formation of surfactant-like intermediates, thereby facilitating contact with ozone.

After 18 hours of ozonation, a significant reduction in hydrocarbon species (from 3,211 to 2,183) and nitrogen-containing compounds (from 2,052 to 522) was achieved, particularly for highly unsaturated PAHs.

Another study investigated the efficiency of a combined treatment method for PAH-contaminated soils using ozonation followed by biodegradation to overcome limitations related to bacterial bioavailability of contaminants (*Nam, K. and Kukor, J., 2000*).

The results showed that ozonation is effective in removing low-molecular-weight PAHs such as naphthalene, fluorene, phenanthrene, and anthracene. However, for higher molecular weight PAHs like pyrene, chrysene, and benzo(a)pyrene, the ozonation efficiency was reduced due to their strong binding to soil organic matter and low water solubility (*Nam, K. and Kukor, J., 2000*). Additionally, the presence of organic carbon in the soil (even at low levels, 0.03%) negatively affected the efficiency of the ozone treatment. By applying the combined treatment—ozonation followed by biodegradation—a significant

increase in the degradation of PAHs was observed, including resistant compounds such as chrysene and benzo(a)pyrene, which were not efficiently degraded by the bacterial consortium alone. This increased efficiency was more pronounced in soils contaminated with coal tar, likely due to enhanced bacterial activity (*Nam, K. and Kukor, J., 2000*).

Polycyclic aromatic hydrocarbons (PAHs) are important pollutants, toxic to humans and the environment. Ozone is a strong oxidant capable of transforming PAHs into more soluble and more easily biodegradable compounds. Thus, combining ozonation with biodegradation can increase the removal efficiency of heavy PAHs (*Nam, K. and Kukor, J., 2000*).

The study used sterilized soil and soil contaminated with coal tar, into which seven different PAHs were added. It was demonstrated that the combined ozonation + biodegradation treatment is more effective in eliminating PAHs—including those that are hard to degrade—than biodegradation alone (*Nam, K. and Kukor, J., 2000*). This combined method could be a promising solution for bioremediation of soils contaminated with complex PAH mixtures, such as those from former gasworks.

Combined ozonation and biodegradation treatments for removing PAHs from artificially contaminated soil (*Nam, K. and Kukor, J., 2000*) were tested in two variants: biodegradation followed by ozonation and ozonation followed by biodegradation. Biodegradation lasted 4 weeks, while ozonation was 2 days (Nam, K. and Kukor, J., 2000). In both cases, naphthalene (NAP) and fluorene (FLU) were completely eliminated. For other PAHs (phenanthrene, anthracene, pyrene, chrysene, benzo(a)pyrene), degradation increased by 6–18% compared to ozonation alone. Ozonation followed by biodegradation was more efficient than the reverse order, significantly reducing concentrations of phenanthrene, anthracene, pyrene, and chrysene. Benzo(a)pyrene (BaP) was difficult to degrade, likely due to strong binding to the soil. Ozonation produces oxygenated metabolites that are more water-soluble and biodegradable, thereby facilitating subsequent biological degradation. However, there is a risk that some intermediate metabolites may be more toxic than the original compounds (*Nam, K. and Kukor, J., 2000*). PAH degradation negatively correlates with the number of benzene rings; the larger the ring number, the harder the degradation. Combining treatments offers a better chance for complete contaminant degradation in soil (*Nam, K. and Kukor, J., 2000*).

Ozonation for 2 days effectively reduces light PAHs (NAP, PHE) but not heavy PAHs (PYR, CHR, BaP) (*Nam, K. and Kukor, J., 2000*). Biodegradation alone efficiently degrades light PAHs but struggles with heavy PAHs. Ozonation followed by biodegradation enhances degradation of 4-ring PAHs and partially BaP. BaP degradation remains limited, probably due to low ozone concentration (*Nam, K. and Kukor, J., 2000*). Nutrients are required in soil for effective biodegradation.

Ozone treatment efficiently removed 2-3 ring PAHs but less effectively those with 4-5 rings. By combining ozonation with biodegradation, approximately 95% of NAP, FLU, and PHE and about 65% of PYR and CHR were degraded in contaminated soil. BaP was reduced by ~17%, and combined biodegradation enabled BaP mineralization, which alone was not degradable. This combined method is promising for treating soils contaminated with hard-to-degrade PAHs (*Nam, K. and Kukor, J., 2000*).

The combined ozonation and biodegradation technology represents a promising solution for remediation of soils contaminated with complex PAH mixtures, such as those from former manufactured gas plant sites (*Nam, K. and Kukor, J., 2000*). After prolonged bioremediation, residual petroleum in soil was highly degraded—no alkanes below C14 remained, and concentrations of alkanes and PAHs were much lower than in crude oil. Long-chain alkanes (C34–C40) and 4–6 ring PAHs became predominant, while easily degradable compounds disappeared.

Biomarkers (terpanes, steranes, and triaromatic steranes) were very resistant to bioremediation (losses <35%) (*Wang, J. et al., 2013*). During ozonation (15 hours), total solvent-extractable materials (TSEM) decreased by nearly 69%. Hydrocarbon fractions (saturates, aromatics, and resins) decreased significantly. Ventilation with oxygen without ozone had no effect, indicating ozone's essential role in degradation (Wang, J. et al., 2013). This confirms that ozonation effectively reduces residual hydrocarbons in already bioremediated soils, especially resistant fractions (*Wang, J. et al., 2013*).

Figure 1 shows changes in SARA fractions (Saturates, Aromatics, Resins, Asphaltenes) during ozonation. During the ozonation process of hydrocarbon-contaminated soil, a significant decrease in the total solvent-extractable materials (TSEM) content was observed, reduced by approximately 69% after 15 hours of treatment. This indicates a high efficiency of ozone in oxidizing and decomposing residual hydrocarbons.

Analysis of the SARA fractions (Saturates, Aromatics, Resins, and Asphaltenes) revealed the following changes:

Saturates decreased from 33.6% to 21.6%, indicating degradation of saturated fractions in the soil.

Aromatics decreased from 28.6% to 20.8%, reflecting the oxidation of polycyclic aromatic compounds.

Resins decreased from 36.4% to 28.5%, showing a reduction of intermediate polar fractions.

Asphaltenes increased significantly, from 1.5% to 28.5%, suggesting accumulation of oxygenated and poorly soluble intermediate products formed during ozonation.

These changes indicate that ozonation not only reduces the total amount of hydrocarbons but also transforms chemical structures, leading to the formation of oxygenated compounds with reduced solubility, which may influence subsequent biological degradation (*Wang, J. et al., 2013*).

Figure 2 displays changes in five hydrocarbon groups during ozonation (n-alkanes, terpanes, steranes, PAHs, TAS).

During 15 hours of ozonation, all five groups of hydrocarbons in the soil were degraded to varying degrees:

TAS (Triaromatic Steranes): showed the highest degradation with a 94% removal.

Steranes: decreased by 86.4%.

PAHs (Polycyclic Aromatic Hydrocarbons): reduced by 84.5%.

Terpanes: declined by 80.4%.

Alkanes: experienced the least degradation, with a 59.1% reduction.

The order of reactivity to ozone, from most sensitive to most resistant, was:

TAS > Steranes > PAHs > Terpanes > Alkanes

Although TAS, steranes, and terpanes are typically very stable and resistant to biodegradation, ozonation proved to be an effective treatment for degrading these compounds (*Wang, J. et al., 2013*).

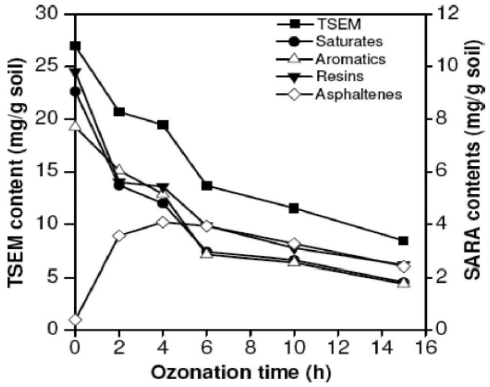

Fig. 1 - Changes in TSEM and SARA Fractions Content During Ozonation

(Wang, J. et al, 2013).

SARA stands for saturated fatty acids, aromatic resins and asphaltenes. TSEM (total solvent extractable matters)

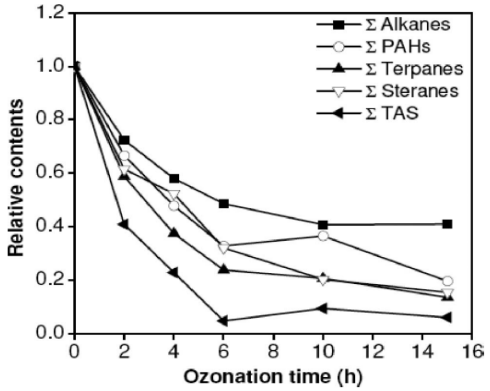

Fig. 2 - Changes in the Content of Five Hydrocarbon Groups (Alkanes, PAHs, Terpanes, Steranes, and TAS) in Soil During Ozonation

(Wang, J. et al, 2013)

TAS - triaromatic steranes

Ozone has been demonstrated to be an effective oxidant for the remediation of soils contaminated with polycyclic aromatic hydrocarbons (PAHs). The reactivity of PAHs with ozone is influenced by the soil

matrix, with higher ozone concentrations enhancing oxidation efficiency, while ozone flow rate appears to have minimal impact. The majority of PAH removal occurs during the initial stages of treatment. Ozone decomposition in soil involves interactions with easily oxidizable organic compounds, stable reaction intermediates, and inorganic soil components, which catalyze ozone breakdown and enhance the overall oxidation process (*Rivas, J. et al., 2009*).

Oxidative treatment is particularly advantageous for PAH-contaminated soils due to the following reasons:

Sole extraction methods are insufficient, as they primarily mobilize but do not degrade PAHs.

Bioremediation is cost-effective and environmentally friendly but limited by the strong sorption of PAHs to soil particles, resulting in slow degradation rates.

Chemical oxidation offers:

Rapid reaction kinetics.

Access to otherwise biologically inaccessible contaminants.

Applicability in situ, on site, or ex situ.

Transformation of hydrophobic PAHs into more soluble and biodegradable oxidation products.

However, chemical oxidation has drawbacks, including higher operational costs relative to bioremediation, potential reagent losses, and the need for careful management of solvents and secondary reaction products.

Common oxidative technologies include ozone treatment, Fenton's reagent, supercritical water oxidation, permanganate, and persulfate oxidation. For enhanced remediation performance, a combined approach integrating chemical oxidation as a pretreatment step followed by bioremediation as a polishing step is recommended. According to Rivas (2006), soil remediation using ozone is a versatile technology deployable in situ, on site, or off site.

Ozone can be introduced as a gas or aqueous phase, with gaseous ozone exhibiting superior diffusivity and higher local concentrations, thus improving contaminant destruction efficacy, especially for PAHs. Ozone treatment efficiency diminishes with increasing soil moisture content, highlighting the necessity of thorough soil characterization to optimize ozone distribution and prevent preferential flow paths that cause uneven treatment. Reaction rates of PAHs with ozone are slower in soil matrices compared to aqueous systems.

Additionally, soil organic matter and metal oxides can modulate ozone consumption; these components may facilitate the generation of highly reactive hydroxyl radicals, further accelerating oxidation processes.

Table 1

Ozone soil remediation technologies

Variables studied	Parameters measured	PAHs oxidised	Notes	References
Combination of chemical oxidation +biodegradation	PAH removal, biodegradability	Fluoranthene, phenanthrene, fluorene, pyrene, triphenylene, benz(*a*)anthracene, chrysene	In the single ozonation process, high molecular weight PAHs exhibit higher removal efficiency compared to low molecular weight PAHs. Conversely, biodegradation experiments show greater degradation rates for low molecular weight PAHs than for their high molecular weight counterparts.	Kulik, N. et al, 2006
Two and three phases ozonation, soil nature, PAH molecular weight	PAH removal, biodegradability	Phenanthrene, anthracene, fluoranthene, pyrene, triphenylene, benz(*a*)anthracene, chrysene, perylene, benzo(*e*)pyrene, benzo(*a*)pyrene, benzo(*g*,*h*,*i*)perylene	Two-phase ozonation demonstrates higher efficiency compared to three-phase ozonation. The combined treatment of ozone followed by biodegradation proves to be effective for remediating contaminated soils. PAHs with a lower number of aromatic rings	Goi,A. and Trapido, M. 2006

			are more readily degraded than their higher molecular weight counterparts.	
Soil nature, radical scavengers, zone dose, humic substances	PAHs removal,ozone uptake	Phenanthrene, benzo(*a*)pyrene	Ozone dosage exhibits a positive effect on the treatment efficiency, while the presence of tert-butanol and humic substances negatively impacts the process. The influence of carbonates is inconclusive, showing no definitive trend.	Choi, H. et al, 2001
Presence of organic matter, soil moisture, soil texture	Ozone demand, PAH removal, toxicity	Pyrene, naphthalene, chrysene, phenenthrene	Soil moisture increases the ozone demand compared to dry soils. The rate of PAH ozonation in soil is lower than expected based on aqueous-phase experiments.	Masten, S.J. and Davies SHR, 1997
Feasibility to treat sediments from a freshwater boat slip subjected to coal tar contamination	PAH removal, biodegradability, chemical oxygen demand, by-products	Naphthalene, phenanthrene, pyrene, benzo[*a*]pyrene	A 2-hour ozonation treatment achieves 50–100% removal of various PAHs present in both the solid and aqueous phases of the sediment. The ozonation process alters the sediment's organic and inorganic composition. Additionally, ozonation enhances the biodegradability of the contaminants, making an integrated chemical-biological remediation approach a viable and effective strategy.	Zeng, Y., and Hong P.K.A. 2002

CONCLUSIONS

This study demonstrates the effectiveness of both direct and indirect oxidation mechanisms during ozonation in treating soils contaminated with complex mixtures of PAHs and organic matter. The presence of organic solvents such as toluene enhances remediation by increasing contaminant bioavailability and facilitating oxidation reactions.

Ozone efficiently degrades not only easily oxidizable fractions but also highly resistant hydrocarbon biomarkers, making it a promising technology for reducing residual hydrocarbons in contaminated soils.

During ozonation, saturated compounds, aromatics, and resins undergo transformation, while the observed increase in asphaltenes indicates the formation of partially oxidized, poorly soluble intermediate products.

The combined ozone-biological treatment represents an optimized approach for remediating soils contaminated with complex PAH mixtures, achieving higher degradation rates compared to individual methods.

In the absence of an organic solvent, the efficiency of direct ozonation is limited due to strong contaminant adsorption onto the soil matrix. The addition of toluene promotes contaminant mobilization through desorption and surfactant-like intermediate formation, enhancing contact with ozone.

After 18 hours of ozonation in the presence of toluene, a significant reduction of hydrocarbon and nitrogen-containing compounds was observed, particularly for highly unsaturated PAHs, confirming the potential of this treatment for persistent soil pollution remediation.

ACKNOWLEDGEMENT

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BIOREMEDIATION OF SOILS CONTAMINATED WITH HYDROCARBONS USING MICROBIAL CONSORTIA

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BIOREMEDIEREA SOLURILOR CONTAMINATE CU HIDROCARBURI UTILIZÂND CONSORȚII MICROBIENE

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ABSTRACT

The petroleum industry is one of the major industrial sectors, and its activities lead to the pollution of agricultural land. Environmental pollution associated with petroleum hydrocarbons, and their refined products is a serious concern because it harms the ecosystems, human health, groundwater quality and soil fertility. The main soil pollutants include polycyclic aromatic hydrocarbons, petroleum and related products, pesticides, chlorophenols and heavy metals. Polluted soil can be remediated using both biological and physico-chemical methods. Among the treatment methods, bioremediation has gained particular attention because it is an economical, effective and environmentally friendly method of remediation for soils contaminated with petroleum hydrocarbons. This review focuses on the bioremediation of hydrocarbon-contaminated soils using microbial consortia. In addition, the main classes of petroleum hydrocarbons, the types of microorganisms involved, and the bioremediation techniques applied to hydrocarbon-polluted soils are described.

REZUMAT

Industria petrolieră reprezintă unul dintre principalele sectoare industriale, însă activitățile sale conduc la poluarea terenurilor agricole. Poluarea mediului asociată cu hidrocarburile petroliere și produsele lor rafinate reprezintă o preocupare serioasă, deoarece afectează ecosistemele, sănătatea umană, calitatea apelor subterane, precum și fertilitatea solului. Principalii poluanți ai solului includ hidrocarburile aromatice policiclice, petrolul și produsele conexe, pesticidele, clorofenolii și metalele grele. Solul poluat poate fi remediat utilizând atât metode biologice, cât și metode fizico – chimice. Printre metodele de tratament, bioremedierea a câștigat o atenție deosebită datorită faptului că este o metodă de remediere a solurilor contaminate cu hidrocarburi petroliere economică, eficientă și ecologică. Acest review tratează bioremedierea solurilor contaminate cu hidrocarburi utilizând consorții microbiene. În plus, în lucrare sunt descrise principalele clase de hidrocarburi petroliere, tipuri de microorganisme utilizate în procesul de bioremediere, precum și tehnici de bioremediere utilizate pentru solurile poluate cu hidrocarburi petroliere.

INTRODUCTION

Lately, the pollution of agricultural lands has become a major problem worldwide and is associated with industrial development. The oil industry is one of the major industrial sectors and its activities lead to the pollution of agricultural lands. The environmental pollution associated with petroleum hydrocarbons and their refined products is a serious concern as it affects the ecosystem and human health, groundwater quality and soil fertility *(Varjani, S., Upasani, V. N., Pandey, A., 2020).*

Due to the huge demand as an energy source, contamination with petroleum hydrocarbons occurs quite often as a result of exploration, production, maintenance, transportation, storage, and accidental release, leading to significant environmental impacts (*Ahmed F., Fakhruddin A.N.M., 2018*). Petroleum hydrocarbons and heavy metals are classified as major pollutants that represent a serious environmental threat *(Haque, S., Srivastava, N., Pal, D.B. et al, 2022).*

The concentration of total petroleum hydrocarbons in soil was reported to be approximately 44,600 mg/kg dry soil. Total petroleum hydrocarbons are composed of aliphatic hydrocarbons and aromatic compounds, which have harmful effects on humans and other organisms. In addition, oil released on soils

involves serious pollution problems *(Feng, L., Jiang, X., Huang, Y. et al, 2021)*. When entering the soil, hydrocarbons alter soil properties such as electrical conductivity, pH, hydrophobicity, destroy soil texture and structure, or may affect soil biological properties, in particular microbial population and enzyme activity, indirectly affecting the availability of nutrients to plants *(Ambaye, T.G., Chebbi, A., Formicola, F. et al, 2022)*.

Polluted soil can be remediated using both biological and physical-chemical methods. Biological techniques are more energy-efficient than physico – chemical methods, but less effective in treating oil spills. Some forms of micro-organisms can break down oil and use it as a source of carbon and energy. The unique breakdown of hydrocarbons into simpler products is due to the genetic characteristics of microbes (*Ajona, M., Vasanthi, P., 2021*). Among the treatment methods, bioremediation has gained particular attention because it is an economical, efficient and environmentally friendly method to remediate soils contaminated with petroleum hydrocarbons *(Feng, L., Jiang, X., Huang, Y. et al, 2021)*.

Microbial communities, such as heterotrophic bacteria and fungi, can metabolize and convert complex petroleum hydrocarbon-based pollutants into simple, less toxic forms and are widely used as bioremediation agents to remove petroleum hydrocarbons from the environment *(Ambaye, T.G., Chebbi, A., Formicola, F. et al, 2022)*. Microbial consortia have a higher degradation capacity than a single microbial species, the use of a single micro-organism limits the efficiency of the process *(Lázaro-Mass, S., Gómez-Cornelio, S., Castillo-Vidal, M. et al, 2023)*.

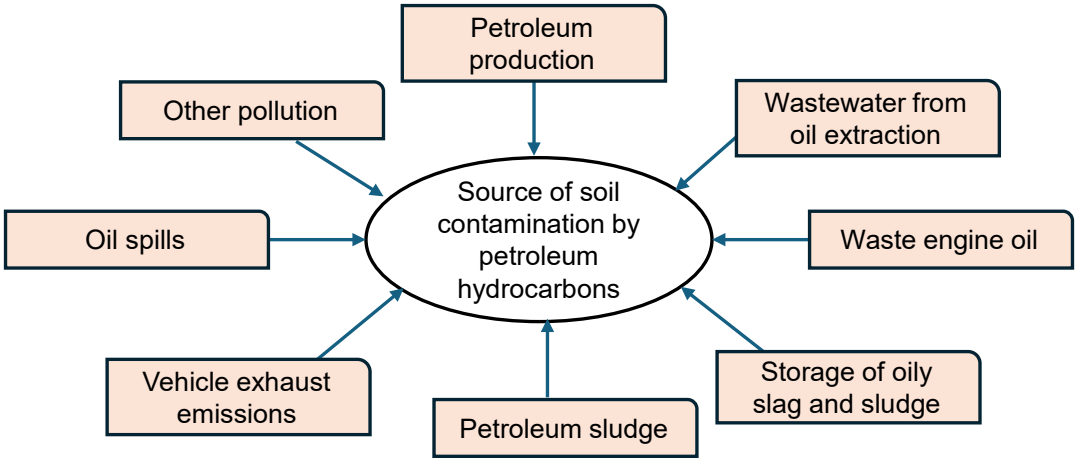

Fig. 1 - The main sources of soil contamination by petroleum hydrocarbons
(adapted from Ambaye, T.G., Chebbi, A., Formicola, F. et al, 2022 and Sui, X., Wang, X., Li, Y. et al, 2021)

The present review focuses on the bioremediation of hydrocarbon contaminated soils using microbial consortia. In addition, the main classes of petroleum hydrocarbons, types of microorganisms used in the bioremediation process, and bioremediation techniques used for hydrocarbon-polluted soils are described.

CLASSIFICATION OF PETROLEUM HYDROCARBONS

Petroleum hydrocarbons as contaminants are a highly toxic mixture of paraffinic, aliphatic and aromatic compounds and have become a serious environmental concern because of their ability to pollute soil and water (*Ambaye, T.G., Chebbi, A., Formicola, F. et al, 2022*).

Total petroleum hydrocarbons (TPH) include *(Mekonnen, B. A., Aragaw, T. A., Genet, M.B., 2024; Ferdeș, M., Dincă, M. N., Istrate, I. A. et al, 2024)*:

1. saturated hydrocarbons (aliphatic)
2. aromatic fraction
3. resins
4. asphaltene.

In general, the structure of petroleum hydrocarbons consists of about 57% aliphatic hydrocarbons, followed by about 29% aromatic hydrocarbons and about 14% as asphaltenes with various polar compounds *(Haque, S., Srivastava, N., Pal, D.B. et al, 2022)*. Based on their chemical structure, saturated hydrocarbons are classified into groups including alkanes (paraffins) and cycloalkanes (naphthenes). Longer chain aliphatic hydrocarbons (C20-C40) are more persistent in soil, do not volatilize easily and are difficult to degrade due to their low water solubility, biological availability and structure *(Koshlaf, E., Ball, A.S., 2017)*.

There are two main categories of compounds: volatile petroleum hydrocarbons and petroleum extractable hydrocarbons. The first group includes short-chain hydrocarbons (C6-C10), which include

benzene, toluene, ethylbenzene and xylene (BTEX). The second group includes long-chain aliphatic hydrocarbons (C10-C40) and polycyclic aromatic hydrocarbons (PAHs) *(Mayans, B., Anton-Herrero, R., García-Delgado, C. et al, 2024)*. These contaminants cause physico-chemical changes in soil properties such as texture, moisture, conductivity, total organic carbon, permeability and compaction and as well as in the biological properties (biomass and enzymes) *(Daâssi, D., Almaghribi, F. Q., 2022)*. In addition, through the soil and, consequently, through plants, these contaminants can be introduced directly into the food chain and are capable of altering physiological or biological processes in many species, including humans, thereby causing serious chronic diseases. In addition, of the various contaminants of petroleum hydrocarbons, BTEX compounds are known to be the most toxic *(Haque, S., Srivastava, N., Pal, D.B. et al, 2022)*. The main soil pollutants include PAHs, petroleum and related products, pesticides, chlorophenols and heavy metals *(Chen, M., Xu, P., Zeng, G. et al, 2015)*.

BIOREMEDIATION TECHNIQUES FOR PETROLEUM HYDROCARBONS POLLUTED SOILS

Soil contamination with petroleum products is a major problem for both the environment and public health, with global implications. Naturally, the process of petroleum degradation in contaminated soil is slow, and complete removal of contaminants is often impossible to achieve. Currently, contaminated soil remediation is achieved through a variety of techniques, including physical methods such as incineration, thermal desorption, landfilling, and electrokinetic treatment, as well as chemical methods such as chemical oxidation and washing extraction *(Yan, Z. F., Fei, Y., Wang, Z. Q. et al, 2024)*. Given the adverse effects associated with other methods, bioremediation has gained considerable attention in recent years, as it is considered a more environmentally friendly alternative.

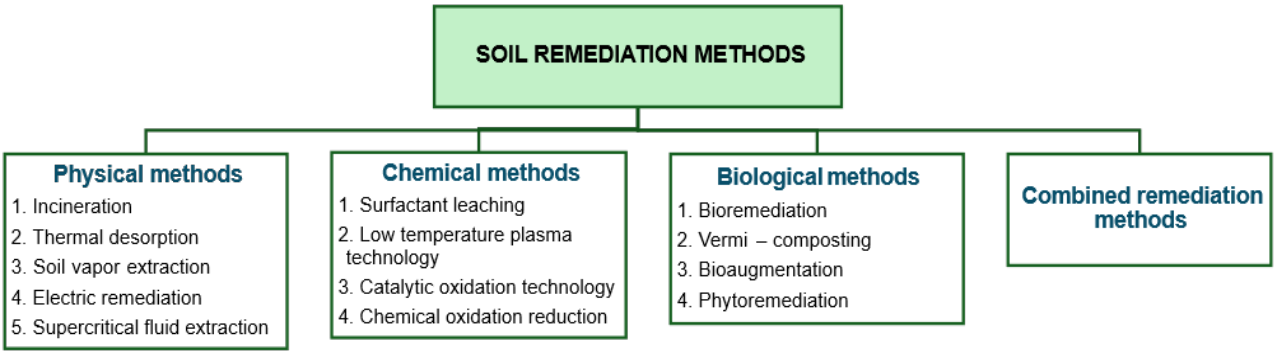

Fig. 2 - Remediation methods for petroleum contaminated soils
(based on Lv, Y., Bao, J., Zhu, L., 2022)

Bioremediation (biological remediation) is an effective, economical and environmentally friendly method that has become widely used for the mineralization of organic contaminants in soil and wastewater. Bioremediation is based on microbial metabolic activities in the presence of optimal ecological factors and the necessary nutrients to transform organic pollutants such as petrogenic hydrocarbons. It has been shown in the literature that bacteria, fungi and some microalgae can completely mineralize petroleum hydrocarbons to carbon dioxide (CO_2), water (H_2O), inorganic compounds, cellular proteins and simple organic compounds found in soil and water *(Mekonnen, B. A., Aragaw, T. A., Genet, M. B., 2024; Koshlaf, E., Ball, A. S., 2017)*

Based on the place of application, bioremediation techniques can be grouped into *ex-situ* and *in-situ* bioremediation. Bioremediation methods are economical and environmentally friendly especially when applied *in-situ* (*Alori E.T., Gabasawa A.I., Elenwo C.E. et al, 2022)*.

For *ex-situ* bioremediation methods, the polluted soil is transported from the site of pollution to another site for treatment, considering the concentration of the pollutant, the level of contamination, the type of pollutant, the cost of treatment, and the geographical location of the polluted site. By *in-situ* bioremediation techniques, the pollutants from the soil are removed right at the pollution site; the soil is treated directly at the pollution site, which makes the method more cost-effective than *ex-situ* bioremediation techniques. Some *in-situ* bioremediation techniques are enhanced by the microbes present in the polluted soil (*Alori E.T., Gabasawa A.I., Elenwo C.E. et al, 2022; Hussain, A., Rehman, F., Rafeeq, H. et al, 2022*).

Different types of biological remediation methods are used to treat hydrocarbon polluted soils. The classification of the bioremediation techniques is presented in Figure 3.

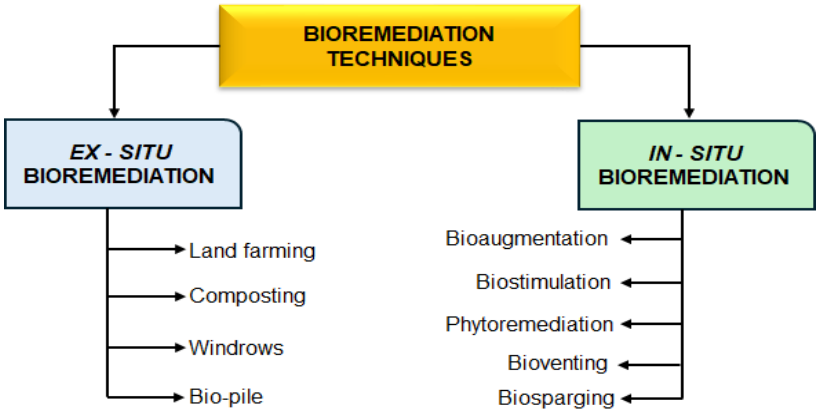

Fig. 3 - Bioremediation techniques for petroleum hydrocarbons polluted soils
(adapted from *Mekonnen, B. A., Aragaw, T. A., Genet, M. B., 2024; Alori E.T., Gabasawa A.I., Elenwo C.E. et al, 2022; Koshlaf, E., Ball, A. S., 2017)*

The choice of bioremediation method depends on different factors including: the affected area, the type, concentration and nature of the pollutant, the cost of remediation method, the depth of contamination, environmental policies, oxygen concentrations, ambient temperature, soil characteristics, amount of nutrients and soil pH and moisture (*Koshlaf, E., Ball, A. S., 2017; Alori E.T., Gabasawa A.I., Elenwo C.E. et al, 2022; Micle, V., Sur, I.M., 2021*).

Bioremediation strategies are based on the introduction of nutrients and oxygen to stimulate the growth and activity of native microflora (biostimulation) or the addition of previously selected indigenous or genetically modified microflora to support native microbial species (bioaugmentation). In biostimulation, nutrients, O_2 or other oxidizing agents are added as biostimulants to stimulate the growth of indigenous microorganisms to remove contaminants. Nutrients such as nitrogen (N), phosphorus (P) and potassium (K) are essential for the successful biodegradation of petroleum hydrocarbons. Studies have shown high removal efficiency of total petroleum hydrocarbons (TPH), n-alkanes or PAHs after spraying nutrient-enriched liquid solution on contaminated soils *(Tsai, W. H., Chen, T. W., Liu, Y. H. et al., 2025).*

For example, Tsai W.H. *et al, (Tsai, W. H., Chen, T. W., Liu, Y. H. et al., 2025)* tested two biostimulants, soil bioremediation nutrients (SBNs) and nutrient solution (NS), in order to assess their effects on the degradation of petroleum hydrocarbons from contaminated soil and changes in bacterial community compositions. Their results indicated that the highest total petroleum hydrocarbons degradation rate (96%) were shown for biopiles with SBNs addition, particularly for 0.5% SBNs – S3), (Figure 4).

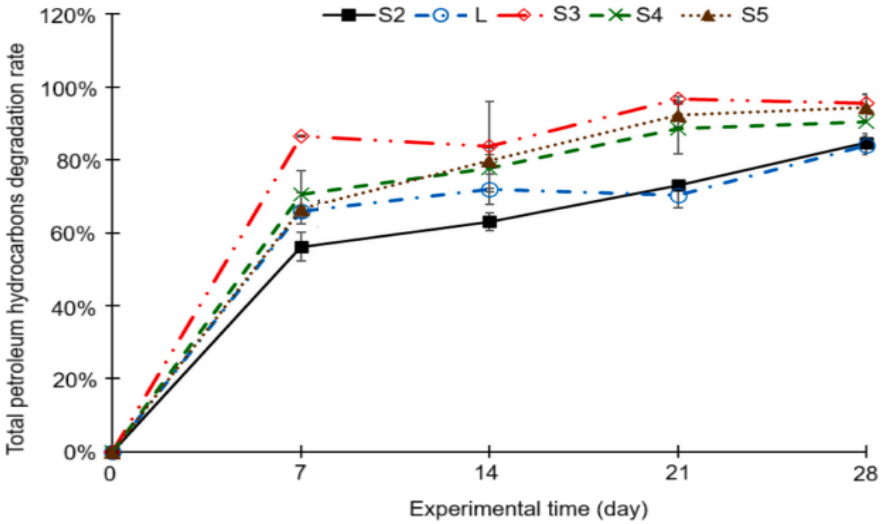

Fig. 4 - Degradation rates of total petroleum hydrocarbons in contaminated soils
(Tsai, W. H., Chen, T. W., Liu, Y. H. et al., 2025)

Michael-Igolima and colab., (Michael-Igolima, U., Abbey, S. J., Ifelebuegu, A. O., 2022) in their study, realised a comparative analysis of remediation methods. As can be seen from figure 5, the combined remediation is the most effective soil remediation method, followed by biological method.

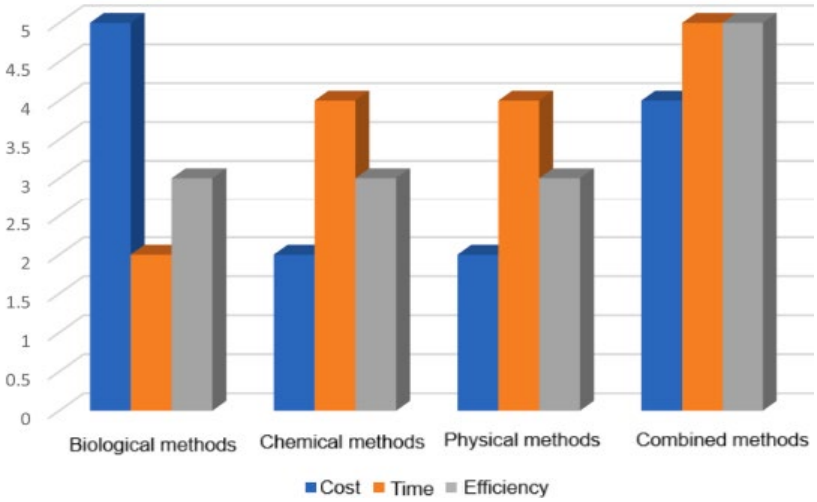

Fig. 5 - Comparative analysis of polluted soil remediation methods
(Michael-Igolima, U., Abbey, S. J., Ifelebuegu, A. O., 2022)

THE USE OF MICROORGANISMS IN THE BIOREMEDIATION PROCESS

The biodegradable degradation of complex hydrocarbons usually involves the collaboration of several bacterial species. This is particularly important in the case of pollutants made up of a variety of compounds (crude oil or petroleum), where the aim is to convert them completely into CO_2 and H_2O *(Ghazali, F. M., Rahman, R. N. Z. A., Salleh, A. B. et al, 2004).*

Microorganisms seem to be the most efficient in the bioremediation process, which can be explained by their structure and size, the diversity of substrates and metabolic pathways involved in the attack on pollutants, and their high resistance to the environmental factors. Depending on the type of pollutants in the bioremediation process, species of bacteria, fungi or microalgae are used single or in combinations (*Ferdeș, M., Dincă, M. N., Istrate, I. A. et al, 2024*).

Among the microorganisms used for the bioremediation process, bacteria occupy the dominant place. In most cases, the native microflora of the polluted area can constitute the source of the microorganisms needed for bioremediation. Among the best-known microorganisms such as bacteria, and fungi that can biodegrade petroleum hydrocarbons are *Aspergillus, Pseudomonas, Trichoderma, Bacillus, Staphylococcus, Penicillium and Rhodotorula (Mekonnen, B. A., Aragaw, T. A., Genet, M.B., 2024).*

Micle and Sur (*Micle, V., Sur, I.M., 2021*), in their research, determined the efficiency of *ex-situ* bioremediation of petroleum hydrocarbon-contaminated soils using a pilot-scale treatment that controls soil aeration time, moisture and microorganism content. During the experiment, they added *Pseudomonas and Bacillus* microorganisms every two weeks. The soil samples were coded according to their location, sampling depth and week in which they were taken (Figure 6).

The authors reported that soils contaminated with petroleum hydrocarbons can be effectively remediated by daily aeration for 8 hours in combination with inoculation of microbial strains of the genera *Pseudomonas* and *Bacillus*. This treatment increases the total number of germs (colony forming units–CFU) from 151 x 10^5 to 213 x 10^7 CFU g^{-1} soil, after 12 weeks of soil treatment, leading to a remediation efficiency of 83%.

In another study, *Varjani et al.* (*Varjani, S., Upasani, V. N., Pandey, A., 2020)* studied bioremediation of soil polluted with petroleum hydrocarbons using a new strain of *Pseudomonas aeruginosa* NCIM 5514. The authors compared five different methods for remediation of polluted soil, namely: bioaugmentation + biostimulation, bioaugmentation, biostimulation, natural attenuation and abiotic factors. In addition, they studied germination of *Vigna radiata* (mung bean) using natural agricultural soil, polluted agricultural soil and bioremediated agricultural soil.

The results showed that the degradation of hydrocarbons was greatest when *Pseudomonas aeruginosa* NCIM 5514 and nutrients were added to the microcosms at the same time, compared with the use of abiotic factors, bioaugmentation, biostimulation, and natural attenuation separately. The results also showed that the bioremediation approach improved seed germination in soil contaminated with oily sludge.

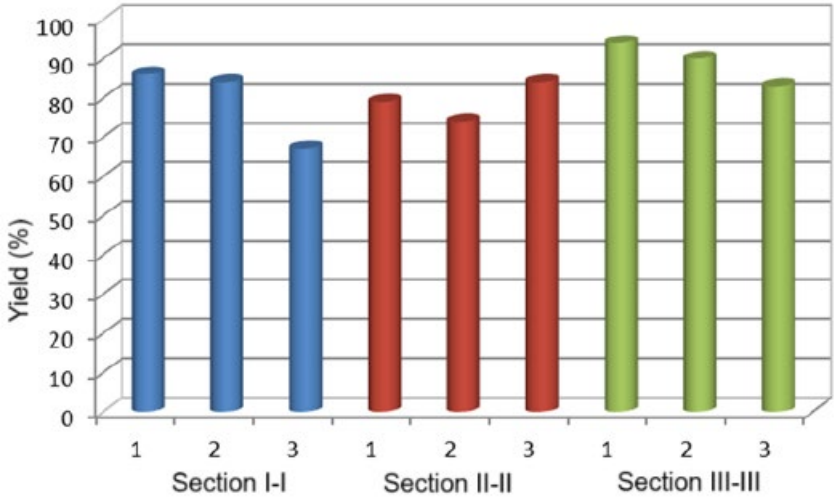

Fig. 6 - Depollution efficiency for petroleum hydrocarbons contaminated soils

(Micle, V., Sur, I.M., 2021)

In the study conducted by *Ma X.k et al. (Ma, X. k., Mao, D., Chen, J. et al, 2024)*, different fungal-bacterial consortia were analyzed, as well as inoculation strategies applied in soils contaminated with petroleum sludge with a total petroleum hydrocarbon concentration of 124,000 mg/kg. Their results demonstrated that strategies using sequential inoculation, with one dose administered at the beginning and another on day 30, of a consortium consisting of either *Bacillus sp.* and *Acremonium sp.* (treatment 1) or *Bacillus sp.* and *Phanerochaete sp.* (treatment 3), had a higher removal efficiency compared to discontinuous inoculation treatments.

Removal of total petroleum hydrocarbons in a pilot system (*on-site*) was investigated by *Martínez-Rabelo F. et. al (Martínez-Rabelo, F., Gómez-Guzmán, L. A., García-Segura, D. R. et al, 2023).* A combination of three simultaneous technologies was applied to oil-contaminated soil, namely: bioaugmentation (bacterial consortium: *Bacillus* sp., *Pseudomonas* sp., and *Shigella* sp.), phytoremediation (*Panicum maximum* grass), and vermiremediation (*Pontoscolex corethrurus* earthworm*)*. Bioremediation treatments were compared with natural attenuation. Authors reported that after 112 days, the bioremediation treatments significantly removed more alkanes (76%), polycyclic aromatic hydrocarbons (68%), and total petroleum hydrocarbons (76%) compared to the natural attenuation treatment (23%, 19%, and 24%, respectively).

Sharma et al. (2016) (Sharma, A., Singh, S. B., Sharma, R. et al, 2016) describe the use of a microbial consortium consisting of *Serratia marcescens* L-11, *Streptomyces rochei* PAH-13, and *Phanerochaete chrysosporium* VV-18 for the *in-situ* bioremediation of polyaromatic hydrocarbons. Within 7 days, the polyaromatic hydrocarbons degradation rate significantly increased to 56–98% under *in-situ.*

CONCLUSIONS

Soil contamination with petroleum products is a major problem for both the environment and public health, with global implications. Naturally, the process of petroleum degradation in contaminated soils is slow, and complete removal of contaminants is often difficult to achieve.

Bioremediation is a non-invasive and cost-effective technology used to remediate sites polluted with petroleum compounds. This method is widely used because it is applicable over large areas and can significantly reduce the concentration of contaminants. The biodegradation process carried out by natural microbial consortia is one of the main mechanisms for removing petroleum and other hydrocarbon-based pollutants from the soil and is cheaper than other remediation technologies.

ACKNOWLEDGEMENT

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research, development and innovation, I5 Establishment and operationalization of Competence Centers) and by *the project CNFIS-FDI-2025-F-0108 "Ensuring the sustainability of an application base for biotechnical systems in orchards, vineyards, gardens and solariums (SISBIOSUS)", from the Ministry of Education and Research through the Executive Agency for Financing Higher Education, Research, Development and Innovation.*

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ENGINEERING MEASURES FOR SOIL EROSION CONTROL: A MECHANISM-BASED SYNTHESIS

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CONSIDERAȚII PRIVIND PRINCIPALELE METODE UTILIZATE ÎN CONTROLUL EROZIUNII SOLULUI

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Keywords: *vegetative cover, organic and biodegradable mulching, geotextile silt fences, check dams, biopolymer soil stabilization, runoff attenuation; sediment yield*

ABSTRACT

Land degradation is a major driver of the decline in agricultural land, dominated by water and wind erosion and by the reduction of soil organic matter. The spread of these processes—amplified by natural and anthropogenic drivers—lowers fertility, strips the upper soil horizon, and increases sediment loads in receiving waters. The paper presents a coherent set of preventive and control measures, grouped by mechanism of action and context of use. We analyze vegetative solutions (cover crops, green manures) and surface protections—organic or biodegradable mulches, geotextile meshes, and rock-fiber blankets—alongside flow-path barriers (check dams, stone berms, silt fences) and near-surface stabilization using chemical/biopolymeric binders to consolidate the topsoil. These directions reflect current trends in erosion control, with emphasis on integration from plot to watershed scale and on maintenance. Defined as permeable barriers installed along contour, silt fences temporarily retain sediment by decelerating overland flow and promoting deposition; effectiveness depends on siting, toe-trenching/anchorage, and routine inspection. In parallel, polymers and biopolymers increase near-surface cohesion and resistance to raindrop impact, creating a stable bed for vegetation establishment while offering a smaller environmental footprint than conventional cementitious agents. The guiding principle is twofold: reduce runoff volume and/or surface velocity, and combine source, pathway, and receptor measures. A decision matrix and monitoring recommendations support adaptive, long-term implementation.

REZUMAT

Degradarea solului reprezintă o cauză majoră a declinului terenurilor agricole, fiind dominată de eroziunea hidrică și eoliană și de diminuarea conținutului de humus. Extinderea acestor procese, amplificată de factori naturali și antropici, conduce la scăderea fertilității, la pierderi de sol superior și la creșterea încărcăturii de sedimente în corpurile de apă. Lucrarea prezintă un set coerent de măsuri pentru prevenirea și controlul eroziunii, grupate după mecanismul de acțiune și contextul de utilizare. Sunt analizate soluții vegetative (acoperire, culturi verzi) și de suprafață — mulcire cu materiale organice sau biodegradabile, plase geotextile și fibre de rocă — alături de bariere fizice pe traseul scurgerii (baraje de control, diguri de piatră, garduri de nămol) și de stabilizatori chimici/biopolimerici pentru consolidarea stratului superficial. Aceste direcții reflectă tendințele actuale în controlul eroziunii, cu accent pe integrarea măsurilor la scară de parcelă–bazin și pe mentenanță. Definite ca bariere permeabile instalate pe contur, gardurile de nămol rețin provizoriu sedimentele prin încetinirea scurgerii și depunere, eficiența depinzând de amplasare, ancorare și întreținere. În paralel, polimerii/biopolimerii pot crește coeziunea și rezistența la impactul picăturilor de ploaie, oferind un mediu stabil pentru instalarea vegetației, cu o amprentă ecologică mai redusă decât lianții tradiționali. Principiul general urmărit este dublu: reducerea volumului de scurgere și/sau a vitezei sale la suprafață, prin combinarea măsurilor de la sursă, pe cale și la receptor.

INTRODUCTION

Ensuring a sustainable and secure food supply is a defining challenge of the twenty-first century as global population approaches nine billion by mid-century; at the same time, agriculture faces intensifying constraints from climate variability and land-degradation processes, especially soil erosion, with documented

impacts on production stability and food prices (*Kumarasinghe, 2021*). Soil erosion—displacement of the fertile upper horizon by natural agents—may proceed gradually and remain unnoticed, or accelerate abruptly under extreme events, stripping substantial volumes of topsoil and mobilizing fine sediments and nutrients (*Psomiadis et al., 2008*).

Classical classifications distinguish natural erosion, driven by water, snow/ice, wind and biotic activity, from accelerated erosion linked to human actions such as deforestation, improper tillage and overgrazing, which markedly increase soil losses (*Koerner, 2005; Psomiadis et al., 2008*).

The consequences propagate from field to watershed: topsoil removal and organic-matter depletion reduce fertility and water-holding capacity, while sediment-laden runoff elevates turbidity, clogs conveyance systems and degrades channels and reservoirs, particularly where fine, non-cohesive soils coincide with high-intensity rainfall (*Psomiadis et al., 2008*). Climate-change stressors—higher temperatures, altered precipitation regimes and more frequent extremes—further depress yields via increased evapotranspiration and flood damage, and interact with recurrent wildfires that remove protective cover, alter soil properties and challenge post-fire recovery (*Wittenberg et al., 2023*).

In response, erosion control has increasingly adopted integrated portfolios that combine source, pathway and receptor measures. Geotextile-based sediment barriers (silt fences) remain ubiquitous on disturbed slopes; their performance depends on installation details and hydraulic management rather than fabric filtration alone, as shown by large-flume and full-scale studies (*Farias et al., 2006; Bugg et al., 2017; Whitman et al., 2018; Palmeira, 2020; Koerner, 2005*). Complementary practices include vegetative cover and mulching, contour-aligned interventions, check dams and near-surface stabilization to bridge the establishment period of vegetation (*Kumarasinghe, 2021*).

This paper aims to synthesize principal erosion-control mechanisms and practices (vegetative cover, mulching, geotextile sediment barriers, check dams and near-surface stabilization), relate them to site and climate contexts, and provide a decision-oriented framework—consistent with the article's own reference list—for selecting, sizing and maintaining effective, context-appropriate measures.

MATERIALS AND METHODS

One cause of the decline in agricultural land is the degradation of soils. The principal processes that drive soil degradation are erosion by water and wind and the decline of soil humus content; when these natural and anthropogenic stressors spread across the landscape, they precipitate a critical loss of soil fertility *(Kumarasinghe, 2021)*. Washing of the upper fertile horizon and the formation of large rills due to improper tillage accelerate topsoil loss *(Psomiadis et al., 2008)*. To prevent soil erosion, field operations should adopt contour-aligned tillage and seeding (i.e., perpendicular to the slope) to shorten flow paths and reduce overland-flow energy *(Kumarasinghe, 2021)*.

Erosion control denotes a portfolio of measures intended to prevent water- and wind-driven erosion during land development and cropping. In practice, water erosion is mitigated by runoff control (e.g., contour practices, check dams, drainage conveyance), while wind erosion is mitigated by reducing near-surface wind speed and protecting the soil against deflation (e.g., residue cover, vegetative barriers) *(Kumarasinghe, 2021; Koerner, 2005)*.

These measures are central to preventing water pollution, soil loss, habitat degradation, financial damages, and asset risks, and are used on farmland, natural areas, and urban settings. In construction and road works, erosion control measures are integral to stormwater programs and slope stabilization, often combining physical barriers (vegetation strips, rock terraces), field and site drainage systems, and sediment controls such as settling basins and silt-fence barriers *(Koerner, 2005; Adachi et al., 2024; Psomiadis et al., 2008)*.

Problems caused by soil erosion and subsequent sedimentation are responsible for significant environmental impacts on reservoir slopes and silted rivers, particularly in regions with intense rainfall and fine, non-cohesive soils *(Toy, Foster, & Renard, 2002)*. *Witheridge (2012)* highlights several primary impacts of erosion and surface runoff: clogging of stormwater pipes and channels, sedimentation and elevated turbidity in receiving waters, splash (raindrop-impact) erosion, and sheet (laminar) erosion.

Accordingly, preventing and controlling erosion is essential to minimize these consequences. In practical terms, erosion control aims to reduce both the gradual and abrupt wear of soil by integrating source, pathway, and receptor measures suited to site hydrology, soil texture, and rainfall regime *(Toy, Foster, & Renard, 2002)*.

A wide array of soil-erosion countermeasures is therefore deployed against water, wind, and other disturbance agents (including livestock and human activity), with current technical trends consolidating the above practices into site-specific, multi-measure portfolios *(Kumarasinghe, 2021)*.

Fig. 1 - Methods used in soil erosion control
(Wittenberg and Shtober-Zisu, 2023)

Figure 2 presents the principal soil-erosion control methods with reference to runoff drivers. Two fundamental approaches are recognized: (1) reducing runoff volume and (2) reducing flow velocity (*Witheridge, 2012; Koerner, 2005*).

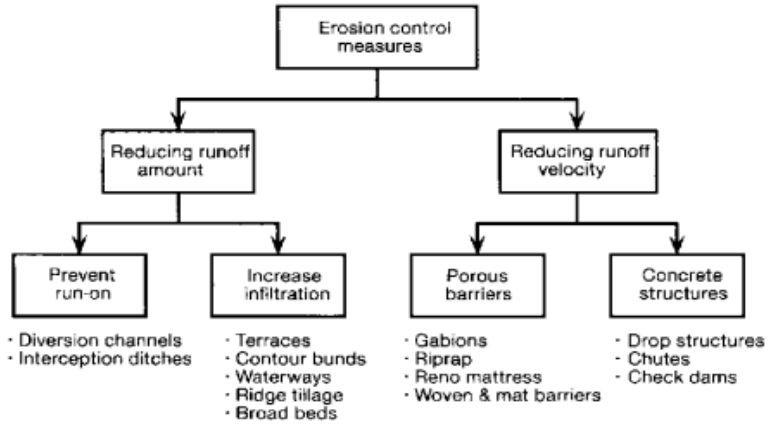

Fig. 2 - Soil erosion control measures
(Witheridge, 2012)

The most effective erosion-control strategy is to minimize the disturbed footprint by preserving as much existing vegetation as possible. This is especially critical on steep slopes or near receiving waters, where no single treatment will adequately control erosion and where receptors are highly sensitive *(Witheridge, 2012)*. Match land development to site sensitivity: avoid wetlands and springs, and exclude areas with steep or fragile soils; delineate and respect all disturbance limits *(Witheridge, 2012)*.

Landslide-hazard management, prevention, and control are essential to reduce risks to life and property; in standard hazard management workflows, mitigation is the final stage that provides the technical means to control natural hazards. Mitigating an existing landslide hazard—or preventing future failures—boils down to reducing driving components and/or increasing resisting forces. The influence of vegetation on slope stability remains an active research challenge, with studies differentiating canopy effects (rain interception, wind shielding) from root-reinforcement mechanisms, while also emphasizing the role of surface runoff over vegetative cover *(Kumarasinghe, 2021)*.

Rainfall-generated overland flow is a practical indicator of slope water loss: it occurs when rainfall intensity exceeds infiltration capacity, producing excess water that cannot infiltrate *(Toy, Foster, & Renard, 2002)*. In this context, implementing sediment-control systems (e.g., sediment barriers) is typically far less costly than repairing downstream damage *(Witheridge, 2012; Adachi et al., 2024)*.

A range of measures is available for erosion control—including mulching, contour seeding, check dams, soil amendments, stone berms, chemical stabilizers, and sediment barriers (silt fences) *(Witheridge, 2012; Koerner, 2005)*. Geosynthetics specifically designed for erosion control have become increasingly

common; their efficiency has been evaluated in both laboratory and field programs *(Farias, Palmeira, & Carvalho, 2006; Adachi et al., 2024)*.

A silt fence is a linear, contour-aligned temporary sediment barrier composed of geotextile supported by wood or metal posts; it slows sheet flow and promotes deposition from disturbed soils on construction sites. The method is cost-effective and readily removable *(Witheridge, 2012; Koerner, 2005; Farias, Palmeira, & Carvalho, 2006)*. Performance depends primarily on siting, toe-trenching/anchorage, and maintenance; large-scale tests show that structural configuration governs sediment capture *(Bugg, Zech, & Perez, 2017; Whitman, Zech, & Donald, 2018; Adachi et al., 2024)*.

Among the constituent materials, geotextiles are central. Over the last five decades, geotextiles have been used as filters because they offer cost and environmental advantages over granular filters *(Koerner, 2005; Palmeira, 2020)*. Filtration is the retention of soil particles subjected to hydrodynamic forces while allowing fluid passage through or around the geosynthetic; filtration behavior depends on hydraulic conditions and soil characteristics (particle-size distribution, density, plasticity), and differs between woven (predominantly two-dimensional pore network) and nonwoven (three-dimensional thickness-scale flow paths) geotextiles *(Palmeira, 2020; Koerner, 2005)*.

Design and construction guidance for silt-fence systems emphasizes configuration, hydraulic capacity, and maintenance; full-scale and flume studies document the benefits of improved anchorage details, post spacing, and controlled dewatering to limit undermining and overtopping *(Whitman, Zech, & Donald, 2018; Bugg, Zech, & Perez, 2017; Farias, Palmeira, & Carvalho, 2006; Adachi et al., 2024)*.

Mulching—the application of materials such as residue, biodegradable films, or mineral cover prior to, during, or immediately after seeding—targets reduced evaporation and water-erosion, improved soil temperature and water-supply capacity, and weed suppression, thereby improving crop production and reducing water use *(Kumarasinghe, 2021)*.

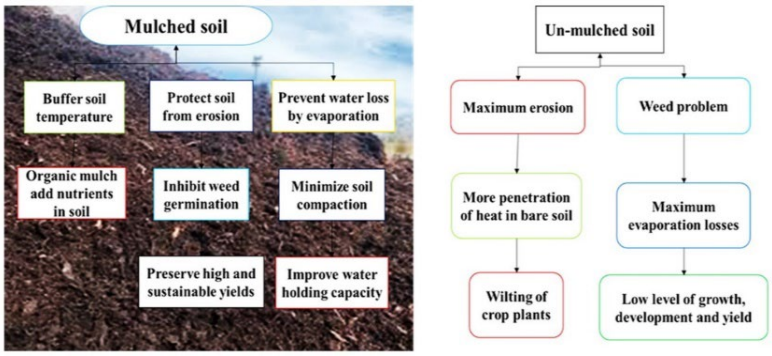

Fig. 3 - Comparative approach with mulched and unmulched soil/crops
(Kumarasinghe, 2021)

Mulch materials are commonly grouped into three classes: organic, inorganic, and specialty. Organic mulches are produced from agricultural residues, wood-processing by-products, processed plant wastes, and animal manures (*El-Beltagi et al., 2022*). Inorganic mulches include polyethylene plastic films and other synthetic polymer sheets, while specialty mulches encompass biodegradable and photodegradable films as well as spray-on/bio-based surface covers that improve ease of application and flexibility and are intended as environmentally friendly options (*Kasirajan & Ngouajio, 2012; El-Beltagi et al., 2022*).

Mulching improves soil properties, increases soil-moisture availability, and enhances soil productivity; key effects are summarized in Figure 4 (*El-Beltagi et al., 2022*). In cropped fields, mulching delivers multiple co-benefits: it reduces soil-water loss, suppresses weed germination, dampens raindrop kinetic energy, and limits water-erosion.

Organic mulches foster soil-structure development and stimulate earthworm activity, with knock-on benefits for porosity and infiltration (*Jiménez et al., 2017*). They may also lower soil pH locally and increase nutrient availability as decomposition proceeds, supplying a slow-release nutrient source over time (*El-Beltagi et al., 2022*).

Plastic and biodegradable mulches can improve soil health and pest management by modifying the microclimate and acting as a barrier to splash, thereby reducing fertilizer leaching and keeping nutrients near the root zone for more efficient uptake (*Kasirajan & Ngouajio, 2012; El-Beltagi et al., 2022*).

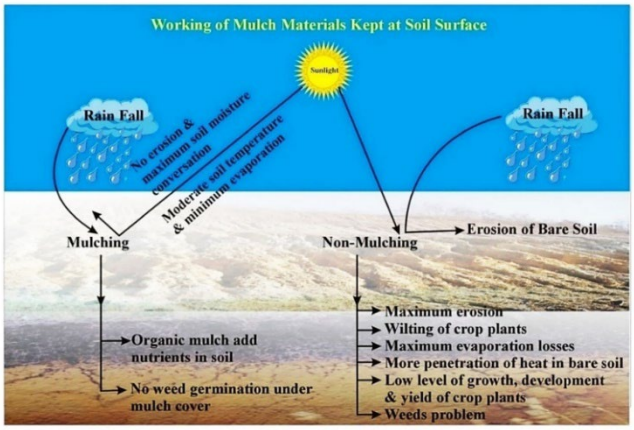

Fig. 4 - Effects between mulching and non-mulching

(El-Beltagi et al., 2022)

In agricultural fields, a wide range of mulching materials is deployed in diverse application modes and layouts, as schematically illustrated in Fig. 5 *(Kasirajan & Ngouajio, 2012; Kader et al., 2017; El-Beltagi et al., 2022)*.

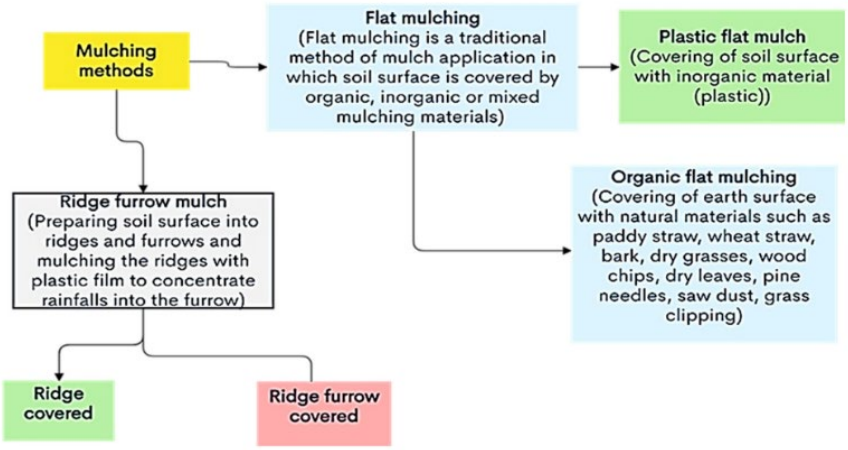

Fig. 5 - An illustration of different mulching techniques

(*El-Beltagi et al., 2022*)

Mulching is widely regarded as beneficial under stressful environments (heat, drought, salinity) because it modifies the evaporation–transpiration balance and the soil–plant microclimate *(Kader et al., 2017)*. Its effectiveness depends on climate and rainfall regime, chiefly by reducing surface evaporation and thus raising near-surface water availability.

In field crops, mulches increase soil-moisture retention, improve soil structure, and suppress weeds, while damping the raindrop kinetic energy that initiates detachment *(El-Beltagi et al., 2022; Jiménez et al., 2017)*. That said, the magnitude of moisture gain varies with mulch material, soil type, and local climate; across studies, mulched treatments generally retain more water than bare soil *(Kader et al., 2017)*.

Over the last decade, substantial research has evaluated traditional soil stabilizers (cement, lime, fly ash, bituminous binders) through direct shear, unconfined compression, and triaxial testing to enhance the strength of natural soils; these approaches can markedly improve mechanical properties but may entail brittle failure modes and environmental trade-offs that limit vegetation establishment *(Chang et al., 2015; Hataf, Ghadir, & Ranjbar, 2018)*.

As an alternative, polymer/biopolymer treatments show attractive mechanical gains with a smaller environmental footprint. Laboratory and field studies report improved resistance to raindrop impact and sheet erosion due to inter-particle bridging and continuous surface coatings; on sandy slopes, water-based polyurethane forms a thin hardened crust that resists rilling under intense rainfall *(Chang et al., 2015; Hataf, Ghadir, & Ranjbar, 2018; Liu, Chen, & Kanungo, 2019)*.

Importantly, eco-engineering trials that pair polymer treatment with vegetation indicate that polymer-treated soils can provide a stable growth medium for seed germination and seedling establishment, supporting integrated stabilization of exposed slopes *(Hataf, Ghadir, & Ranjbar, 2018; Chang et al., 2015)*.

RESULTS

Mulching effectiveness across materials and layouts

Across the reviewed studies, mulching consistently reduced raindrop impact, surface sealing, and net soil loss relative to bare soil. Organic mulches (crop residues, manures, wood by-products) and newer biodegradable films demonstrated higher near-surface water availability by suppressing evaporation; field trials also reported weed suppression and soil structure improvement via increased macroporosity and earthworm activity *(El-Beltagi et al., 2022; Jiménez et al., 2017; Kasirajan & Ngouajio, 2012; Kader et al., 2017)*.

Performance varied with climate and rainfall regime: under hotter/drier conditions the moisture-retention benefit was larger, while under cool/wet regimes thermal moderation and splash reduction dominated. Schematic variants and placement patterns used in agriculture are illustrated in Figs. 4–5 and yielded comparable qualitative outcomes when surface cover exceeded ~60%.

Silt-fence (geotextile) sediment barriers: performance drivers and failure modes

Results from large flume and full-scale testing converge on a central finding: sediment capture is governed mainly by impoundment and controlled dewatering, not by fabric "filtration" alone *(Farias, Palmeira, & Carvalho, 2006; Bugg, Zech, & Perez, 2017; Whitman, Zech, & Donald, 2018; Palmeira, 2020; Koerner, 2005)*. Configurations featuring proper toe-trenching/anchorage, reduced post spacing, and overflow/dewatering elements showed markedly fewer undermining and overtopping events and retained higher fractions of introduced sediment.

Conversely, inadequate trench compaction, long unsupported spans, and uncontrolled bypass led to premature failure. In practice, the placement along contour and the ability to repeatedly store ~0.3 m of ponded water without structural distress were associated with the highest efficiencies.

Geotextile filtration mechanisms relevant to performance.

Nonwoven and woven geotextiles behaved differently under comparable hydraulic and soil conditions: nonwovens provided three-dimensional flow paths through the thickness, whereas wovens relied on two-dimensional pore networks within the plane of the fabric. Effective retention required matching soil gradation and plasticity with apparent opening size and ensuring hydraulic compatibility; where this was satisfied, clogging risk decreased and long-term flow was more stable *(Palmeira, 2020; Koerner, 2005)*. These mechanistic results explain the superior field performance of well-designed systems despite similar nominal fabric parameters.

Vegetation-first and footprint minimization on sensitive sites.

Case syntheses emphasized that minimizing the disturbed area and preserving existing vegetation on steep slopes or near sensitive receptors consistently outperformed any single engineered measure applied post-disturbance. Where disturbance limits were respected and drainage lines/wetlands avoided, the downstream sediment signal and maintenance burden dropped substantially *(Witheridge, 2012)*. These findings support a hierarchy of controls—source measures first (vegetation, mulching), then pathway controls (contour drains, check dams), and finally receptor traps (silt fences, basins).

Polymer/biopolymer and water-based polyurethane (PU) stabilizers.

Laboratory and pilot-scale data showed that low-dosage biopolymers (e.g., xanthan, chitosan) increased near-surface cohesion and delayed rill initiation; treated plots resisted raindrop impact and sheet erosion more effectively than untreated controls *(Chang et al., 2015; Hataf, Ghadir, & Ranjbar, 2018)*. On sandy slopes, water-based PU produced a thin crust that limited rilling during intense storms *(Liu, Chen, & Kanungo, 2019)*. Importantly, pairing polymer treatment with seeding/vegetation provided a stable substrate for germination, indicating that chemical stabilization can bridge the establishment window without the brittleness and ecological trade-offs typical of high-dosage cementitious binders.

Integrated portfolios and cost-avoidance.

Comparative assessments indicated that combined portfolios—mulching + contour interventions + silt-fence trapping—reduced turbidity peaks and sediment delivery more reliably than any single control. Implementing sediment barriers upstream was repeatedly shown to be less costly than post-event remediation of clogged conveyances and silted water bodies *(Witheridge, 2012; Adachi et al., 2024)*. These results reinforce the design principle presented earlier (Fig. 2): pursue runoff-volume reduction and flow-velocity attenuation in tandem for resilient outcomes.

Evidence-based design implications.

(i) Target ≥ 60% post-application surface cover for mulches; anchor on slopes steeper than 1V:3H.

(ii) For silt fences, design for storage and dewatering (height ~0.45–0.60 m; offset trench; robust fastening) rather than relying on fabric filtration alone.
(iii) Select geotextiles by hydraulic/soil compatibility (AOS vs. gradation, plasticity), not just by nominal weight.
(iv) Use biopolymers/PU as temporary surface stabilizers to enable vegetation, with environmental compliance checks. *(Bugg, Zech, & Perez, 2017; Whitman, Zech, & Donald, 2018; Palmeira, 2020; Chang et al., 2015)*.

CONCLUSIONS

Drawing on the experimental evidence and field practice synthesized herein, the following conclusions translate the review into decision-oriented guidance for selecting, sizing, and maintaining soil-erosion controls across source, pathway, and receptor scales.

1. Preserve vegetation and minimize the disturbed footprint first. On steep slopes and near sensitive receptors, preventing disturbance consistently outperforms any single post-disturbance measure. Define and respect disturbance limits; avoid drainage lines and wetlands.
2. Mulching is a high-leverage, low-cost source control—when coverage is sufficient. Target ≥ 60% immediate surface cover; performance scales with climate and rainfall regime. On slopes steeper than 1V:3H, mulch and rolled erosion-control products should be anchored (anchor trench, staples/tackifiers) to prevent wind and runoff displacement.
3. Silt fences work by storage and controlled dewatering, not fabric filtration alone. Efficient systems provide repeatable impoundment (≈ 0.3 m typical), robust toe-trenching/anchorage, reduced post spacing, and overflow/dewatering details to avoid undermining and overtopping. Placement along contour is critical.
4. Select geotextiles by hydraulic compatibility with the soil, not by weight. Woven and nonwoven filters exhibit different pore-network geometries (2-D vs 3-D). Apparent opening size, soil gradation/plasticity, and expected hydraulic gradients govern retention and clogging risk.
5. Polymer/biopolymer and water-based polyurethane (PU) treatments can bridge the vegetation-establishment window. Low-dosage applications increase near-surface cohesion and resistance to raindrop impact/rilling, with fewer brittleness and footprint penalties than high-dosage cementitious binders—provided environmental compliance is verified.
6. Integrated portfolios outperform single measures. Combining source (vegetation, mulch), pathway (contour drains, check dams), and receptor controls (silt fences, basins) reduces peak turbidity and sediment delivery more reliably across site and storm variability.
7. Upstream controls are cheaper than downstream fixes. Proactive sediment barriers and surface protection typically cost less than post-event remediation of clogged conveyances, silted reservoirs, and habitat damage.
8. Design should be decision-oriented and context-specific. Use a matrix keyed to slope, soil texture/plasticity, rainfall intensity, drainage area, and constructability to select feasible measures and their parameter ranges (mulch rate, AOS, post spacing, polymer dosage).
9. Quality assurance and monitoring are non-negotiable. Specify anchor-trench details, fastener density, and installation tolerances; inspect after design storms for ponding depth, dewatering time, fence deflection/undermining, and trapped-sediment height. Maintain photo logs and corrective-action records.
10. Limitations and future work. Field performance remains sensitive to installation quality, maintenance, and extreme-event sequences. Priority research includes (i) long-term field trials for polymer/biopolymer and PU treatments under diverse soils/climates, (ii) standardized dewatering-enabled silt-fence designs for high-intensity rainfall, and (iii) life-cycle and microplastic assessments for mulch materials—particularly biodegradable films.

ACKNOWLEDGEMENT

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THE STAGE OF POSSIBILITY OF SIMPLIFICATION AND MODERNIZATION OF HYDRAULIC SYSTEM CONTROLS FOR COMBINE HARVESTERS

/

STADIUL POSIBILITĂȚII DE SIMPLIFICARE ȘI MODERNIZARE A COMENZILOR SISTEMULUI HIDRAULIC AL COMBINELOR DE RECOLTAT

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***Keywords**: combine harvester, hydraulics components, power steering, ECU.*

ABSTRACT

As the need for greater efficiency, reliability, and ease of maintenance grows, traditional hydraulic control methods often encounter limitations in complexity and flexibility. This study reviews modern control approaches, focusing on electronic and digital innovations, and assesses how feasible it is to incorporate these into existing hydraulic systems. It emphasizes identifying key technological advances, evaluating their effects on system performance, and exploring ways to develop more streamlined, automated control solutions. The results indicate that there are considerable opportunities to reduce the complexity of hydraulic controls while improving their capabilities through digital technologies, leading to more efficient, cost-effective, and widely adaptable hydraulic systems.

REZUMAT

Pe măsură ce nevoia de o eficiență, fiabilitate și ușurință în întreținere sporite crește, metodele tradiționale de control hidraulic se confruntă adesea cu limitări în ceea ce privește complexitatea și flexibilitatea. Acest studiu analizează abordările moderne de control, concentrându-se pe inovațiile electronice și digitale și evaluează cât de fezabil este să le încorporăm în sistemele hidraulice existente. Se pune accent pe identificarea progreselor tehnologice cheie, evaluarea efectelor acestora asupra performanței sistemului și explorarea modalităților de dezvoltare a unor soluții de control mai simplificate și automatizate. Rezultatele indică faptul că există oportunități considerabile de a reduce complexitatea controalelor hidraulice, îmbunătățind în același timp capacitățile acestora prin intermediul tehnologiilor digitale, ceea ce duce la sisteme hidraulice mai eficiente, rentabile și adaptabile pe scară largă.

INTRODUCTION

Modern agriculture is undergoing rapid transformation through the integration of advanced technologies aimed at enhancing productivity and operational efficiency. Among these innovations, automation and digitalization have markedly improved the execution of complex agricultural tasks, thus enabling reduced resource consumption and increased processing speed.

Key examples of this technological advancement include high-performance harvesting machinery, which incorporate sophisticated engineering solutions designed to address the evolving demands of contemporary farming systems.

A critical subsystem within such machinery, particularly in combine harvesters, is the hydraulic system. This system is integral to the operation of numerous components, including the positioning and alignment mechanisms, motion and orientation of cutting devices, transportation, and cleaning of harvested material.

The performance and adaptability of hydraulic systems are therefore vital to maintaining efficient harvesting operations across diverse terrains and varying field conditions *(Blagoi and Mitroi, 2003)*.

Hydraulic Drive System Architecture in Combine Harvesters

The hydraulic drive system in combine harvesters is a critical subsystem that converts hydraulic energy into mechanical energy for the operation of key functional components. This system consists

primarily of a power source (internal combustion engine), a hydraulic pump (generator), and associated auxiliary equipment. The hydraulic pump generates flow by pressurizing a working fluid, which transmits energy to actuators and motors that perform mechanical tasks throughout the machine.

The hydraulic system drives multiple essential assemblies of the harvester, including the reaper, cutting platform, variable speed drive, and steering mechanism. The operation and synchronization of these subsystems are fundamental for efficient harvesting, particularly under varying field and crop conditions.

Reaper Unit (header)

The reaper is responsible for uniformly feeding crop material into the threshing system. Its operation is hydraulically driven, allowing adaptive control under variable terrain and harvesting conditions. Through hydraulic actuation, a coupling attached to the reaper can automatically adjust. to difficult working conditions, such as uneven fields or crops. Hydraulic cylinders modulate the position and angle of the reaper in response to crop density, ensuring a consistent flow of material.

Hydraulic motors enable precise control over rotational direction and speed, enhancing adaptability and efficiency. Coordination with the cutting platform is critical, and modern systems utilize sensors to monitor parameters such as height and speed, allowing real-time adjustments to optimize material intake and reduce loss.

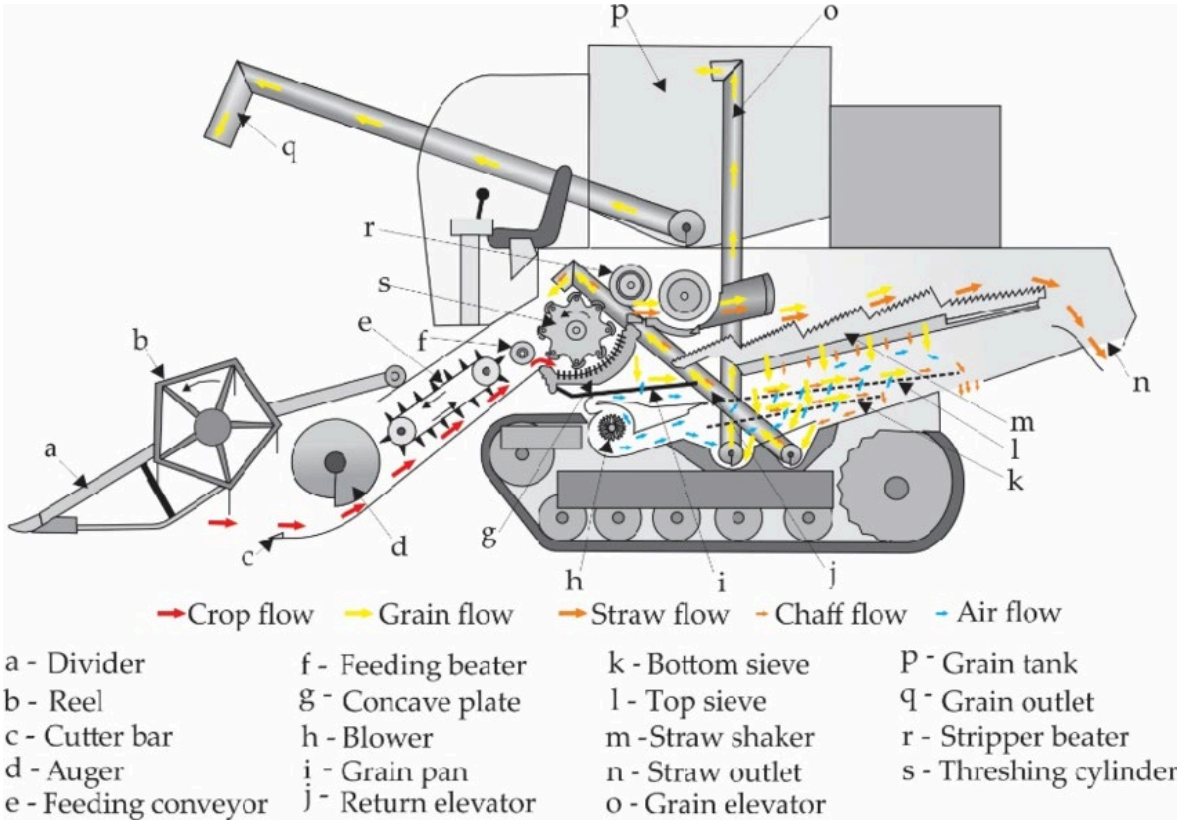

Fig. 1 - Major components and material flow of a combine harvester

(Kahandage et al, 2023)

Cutting Platform

The cutting platform ensures a uniform cut of the crop, which is essential for effective downstream processing. Hydraulic lifting and leveling mechanisms enable dynamic adjustment of the platform height and tilt to maintain optimal cutting conditions across varying terrain.

The cutting blades themselves are often driven by hydraulic motors, which allow fine control over cutting speed based on crop characteristics.

Advanced platforms incorporate parallel guidance systems—mechanical or hydraulic—that enhance stability and tracking performance. Sensor-based feedback systems automatically regulate cutting height and angle in real time, improving efficiency across diverse environmental and operational scenarios.

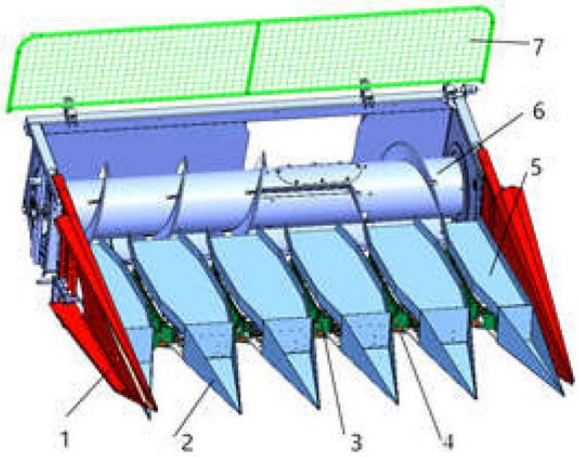

Fig. 2 - Sunflower oil combine harvester header

1-External crop divider. 2-Crop divider header. 3-Clamping and conveying device. 4-Cutting systems. 5-Crop divider. 6-Screw conveyor. 7-Antispatter net.

(Yang et al, 2021)

Variable Speed Drive (Speed Variator)

The variable speed drive system enables adjustment of component functional parameters in response to the specific harvesting conditions and crop types. This functionality is particularly important for optimizing the performance of cutting, threshing, and conveying mechanisms. Speed regulation is achieved by modifying hydraulic pressure through electronically controlled pumps, thereby adjusting the transmission ration in real time.

The system supports dynamic working mode adaptation for components such as the harvester head and cutting blades. For instance, threshing speed can be increased for lighter crop materials or reduced for denser varieties to ensure effective separation without excessive damage.

Power Steering Mechanism

Modern combine harvesters utilize hydraulically actuated steering systems to provide precise rolling, maneuverability and control during operation. A closed-loop hydraulic circuit—comprising pumps, valves, and steering cylinders—facilitates accurate directional changes, even on uneven or sloped terrain.

Steering is typically controlled via a wheel or joystick, which actuates a directional control valve. This input translates into hydraulic pressure that moves the front wheels through connected cylinders. Advanced systems integrate electronic control units (ECUs) and feedback sensors for responsive, real-time steering adjustments, contributing to machine stability and operator ease-of-use *(Catană et al, 1996).*

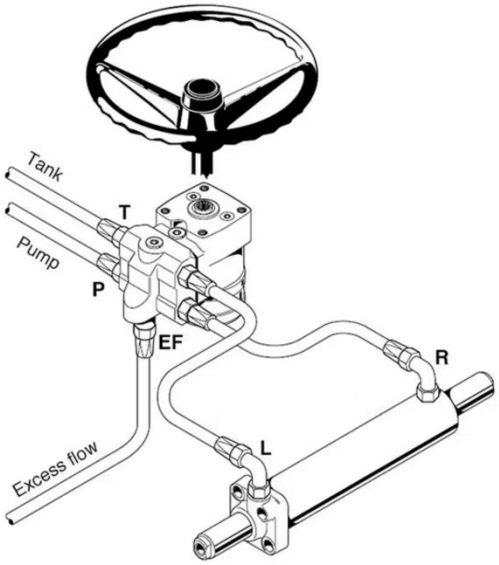

Fig. 3 - Diagram of a hydraulic power steering system

(shijiazhuanghanjiu.en.made-in-china.com)

Integration of Hydraulic Systems Across Functional Subsystems

The hydraulic system functions as the integrative framework that synchronizes the operation of all major components within the combine harvester. Its architecture ensures seamless interaction between the reaper, cutting platform, steering mechanism, and speed variator:

- The reaper and cutting platform operate in tandem to collect and prepare crop material for processing.
- The steering mechanism maintains proper machine alignment in the field, ensuring effective engagement of the harvesting units with the crop rows.
- The variable speed drive ensures optimal synchronization of mechanical components by dynamically adjusting operating speeds based on sensor feedback and crop conditions.

The interdependence of these systems underlines the hydraulic system's role as a central coordinating network, vital for achieving high-performance harvesting with minimal energy consumption and material loss.

MATERIALS AND METHODS

Modeling and simulation are fundamental methodologies widely employed in the analysis, comparison, evaluation, and optimization of both the structural and functional parameters of complex systems. In engineered systems, a defined set of input variables is processed to yield specific outputs that fulfill a predetermined operational objective. When such systems are coupled with control mechanisms, they form control systems designed to achieve desired responses and maintain performance levels in accordance with varying input conditions.

In most practical applications, these systems comprise multiple interacting subsystems, each responsible for executing specialized functions in a coordinated manner, either concurrently or sequentially. When system outputs are time-dependent and exhibit continuous variation relevant to real-time operation, the system is classified as dynamic. Agricultural combine harvesters exemplify such dynamic systems due to their involvement in diverse, time-sensitive, and interrelated processes across multiple functional units. These machines are inherently multifunctional and are designed to handle various crop types and field conditions through integrated and coordinated operations.

The effective automation of such systems relies heavily on robust process modeling and control strategies. Emphasis is placed on the development of mathematical models and simulation tools that support the design and real-time control of subsystem functions. These models form the foundation for designing control architectures and physical components, particularly control units, which are central to system automation and performance optimization.

The objective of this study is to contribute to the advancement of knowledge in functional process analysis, mathematical modeling, computer-aided simulation, and automatic control of self-propelled agricultural machinery, with a particular focus on combine harvesters. The complexity of this subject necessitates an interdisciplinary approach that bridges mechanical, electrical, hydraulic, and control engineering domains.

Although the present work does not offer an exhaustive treatment of all related topics, it aims to provide a framework for understanding key concepts, methods, and techniques. Readers are encouraged to engage critically with the content to build a solid foundation for further study and practical application in automated machine design and system integration.

Modern combine harvesters exhibit high material processing capacity, with travel speeds adjustable according to crop type, variety, and soil conditions. To maintain consistent processing performance, the engine typically operates at a constant speed. Simultaneously, the travel speed must be variable, ranging from slow speeds during harvesting to higher velocities for transport on public roads. These operational requirements are met through the integration of multiple energy and drive systems—mechanical, hydraulic, pneumatic, electrical, and electronic—each serving specific roles in propulsion, functional actuation, and control of the harvesting processes.

A considerable portion of the engine's output is allocated not only to the execution of the core technological operations but also to auxiliary systems that enhance operator comfort, such as climate control within the cabin. This underscores the multifaceted nature of modern combine harvesters, which must balance energy efficiency, control precision, and operator ergonomics within a single, highly integrated system *(Nicolae and Coteanu, 1973*).

The control of agricultural machinery operations can be achieved either manually or through automated systems employing various types of controllers. In contemporary combine harvesters, automatic control is predominantly implemented using electrohydraulic actuators, which offer both precision and responsiveness under variable working conditions.

Key functional components of modern combines are increasingly supported by automated control systems designed for load management and process quality assurance. These systems are frequently integrated with visual and acoustic warning mechanisms, enhancing both operator awareness and system safety. For example, monitoring and signaling subsystems are commonly deployed to supervise the operation of conveyors, crop and grain elevators, straw and chaff handling systems, grain storage and transfer mechanisms, threshing units, and straw walkers.

The integration of such signaling and alert systems enables early detection of malfunctions or suboptimal performance, thereby facilitating timely intervention and preventive maintenance. This not only mitigates the risk of severe mechanical failure and financial loss but also contributes to a significant improvement in operational safety and field efficiency. As such, the investment in advanced diagnostic and warning technologies is fully justified by the measurable gains in productivity and system reliability.

Control, regulation, and automation systems within combine harvesters can be classified into several major categories:

- Hydraulic actuation and control systems, responsible for powering and coordinating the mechanical functions of key components.
- Automatic leveling systems, which maintain the horizontal orientation of the header to ensure optimal cutting performance across uneven terrain.
- Steering control systems, which include electrohydraulic power steering mechanisms.
- Automatic regulation systems, which adjust machine parameters in real time based on load or environmental inputs.
- Electromechanical signaling systems, designed to alert operators to abnormal operating conditions.

A notable advancement in steering automation involves the integration of electrohydraulic steering systems with positioning sensors, forming the basis of GPS-assisted navigation systems. These automated steering systems enable precise guidance of the combine during field operation, real-time positional tracking, and data acquisition related to harvesting performance metrics such as crop yield and area coverage.

Such integration of automation, sensor technology, and real-time monitoring represents a key step toward precision agriculture, enabling machines to operate more efficiently, adapt to variable field conditions, and support data-driven decision-making for farm management.

The operation of combine harvesters on uneven terrain presents significant challenges due to their complex structure, variable center of gravity, and the interaction of multiple moving subsystems. These machines must accurately follow predefined trajectories while performing a series of interconnected tasks on crops and plant materials, all while maintaining high standards of work quality and operational efficiency *(Vasiliu N. and Vasiliu D., 2004)*.

In the context of increasing demands for productivity, consistency, and quality control—alongside efforts to reduce variability in human operator performance—there is a growing need for the implementation of automated control systems during field operations. Concurrently, the development of autonomous agricultural vehicles is rapidly advancing, with increasing emphasis on remote operation capabilities. This emerging field envisions remote human supervision combined with autonomous task execution, enhancing both operational flexibility and labor efficiency.

This section has two primary objectives:

1. To outline the general development concept, functional architecture, and block representation of a simulation framework designed to model both the movement of the combine and its operational behavior during field tasks.
2. To propose a flexible and customizable simulation environment that can be adapted by end users according to the specific requirements of their research or application.

The conceptual model underpinning this simulation package has been developed with core principles of modularity, flexibility, and portability in mind. A hierarchical and reconfigurable modular structure allows for the simulation environment to be tailored to various operational modes, including system behavior

analysis and prediction, subsystem testing and validation, operator training, and hardware-in-the-loop or software-in-the-loop simulations *(Miu P., 2016).*

To facilitate advanced simulation and control—whether the equipment is operated via a human-in-the-loop simulator or an autonomous GPS-guided system—a simulation manager must be established. This system component is responsible for the initialization and provision of all essential input parameters, including vehicle configuration, terrain characteristics, processing subsystems, crop type, and spatial positioning data.

The general simulation framework consists of three main modules:

- Data Input Module: Manages the acquisition and preprocessing of simulation parameters.
- Core Simulation Module: Executes the primary computational tasks, including system dynamics, task coordination, and control algorithms.
- Output Module: Presents the results of the simulation, including performance metrics, trajectory data, and system diagnostics.

The simulation manager plays a distinct role in this architecture, separate from traditional human operators or virtual assistants. Within this framework, the simulation manager is tasked with configuring and managing the full range of available simulation options based on user-defined criteria and available datasets. It also oversees the organization, processing, and transmission of these inputs to the core module for real-time or batch simulation execution.

This framework provides a scalable and adaptable toolset for researchers, developers, and equipment manufacturers to analyze and optimize combine harvester behavior under diverse field conditions, supporting the advancement of autonomous and semi-autonomous agricultural technologies.

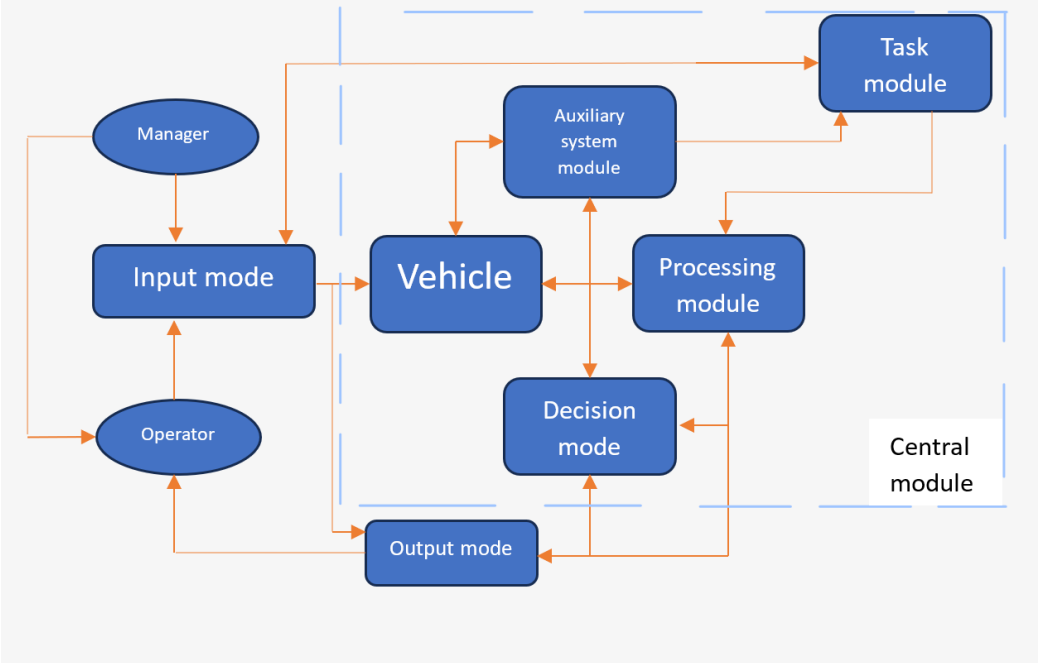

Fig. 4 - Block diagram of a general simulation

For a combine harvester to operate autonomously, it must execute a sequence of complex, interrelated tasks while maintaining a continuous communication interface with a human supervisory system. Upon receiving a pre-programmed task or mission profile from the human operator, the autonomous harvester must be capable of performing the following core functions:

- Automated navigation across mixed environments, including public roadways and agricultural fields, with seamless transitions between the two.
- Autonomous response to dynamic environmental conditions, such as the detection and avoidance of obstacles, adaptation to variable terrain, and interaction with other vehicles or machinery operating within the same environment.
- Self-regulation of harvesting parameters, adjusted in real time based on the specific characteristics of the crop (e.g., density, moisture content, or variety) and local field conditions.

Achieving full autonomy in a combine harvester requires the complete automation of the entire technological workflow—from mobility and perception to processing and decision-making. Such integral automation serves to optimize operational efficiency, ensure consistency in product quality, and support effective harvesting in geographically fragmented or agronomically heterogeneous areas.

The realization of these capabilities relies on the integration of advanced mathematical modeling techniques, real-time control algorithms, and the principles of automatic control theory. Furthermore, the effectiveness of autonomous systems is enhanced by leveraging both internal design expertise and empirical data obtained through extensive field operation.

This convergence of control theory, sensor fusion, artificial intelligence, and mechanized agricultural engineering is pivotal for enabling next-generation autonomous harvesting systems that are not only efficient but also adaptive, robust and scalable to diverse farming scenarios.

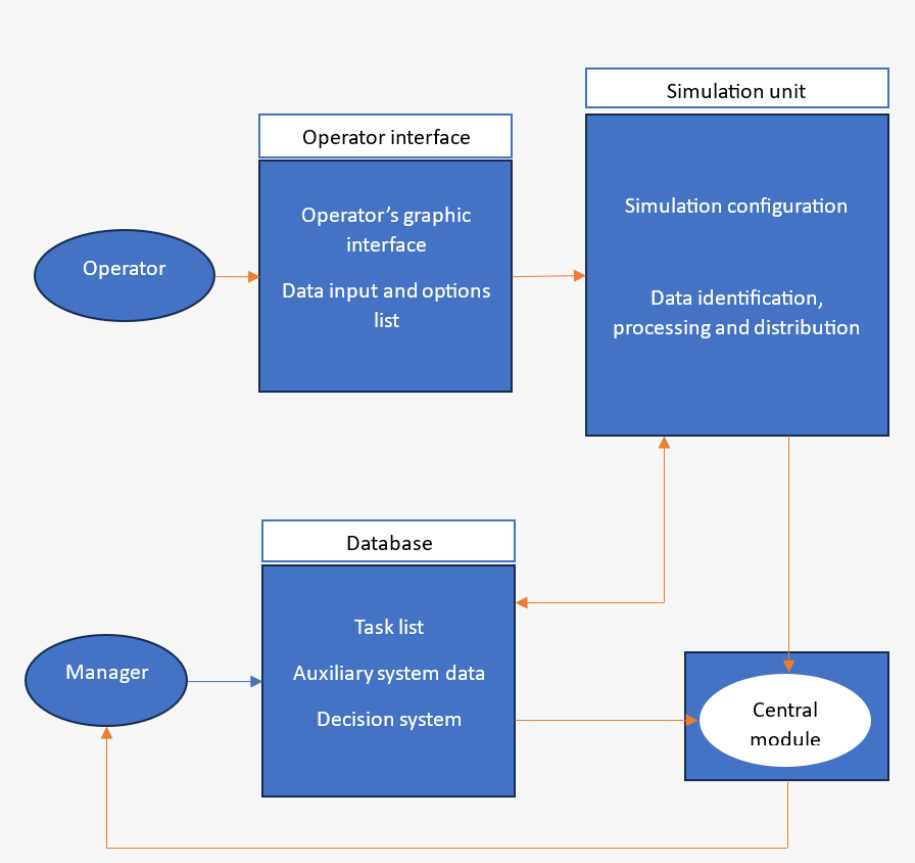

Fig. 5 - Input command diagram

A critical component in the development of autonomous agricultural machinery is the implementation of an automated guidance system capable of accurately controlling the vehicle's direction, speed, and acceleration. To achieve robust and precise navigation under varying environmental conditions, a multi-sensor fusion approach is required—most notably the integration of vision-based systems and satellite-based positioning technologies.

An effective solution involves combining a camera-based visual system with a Global Positioning System (GPS) into a unified control platform. The visual system, utilizing onboard cameras mounted on the agricultural vehicle, enables real-time detection of obstacles and navigational cues without relying on pre-generated digital terrain maps. This system plays a critical role in local navigation and obstacle avoidance, particularly in unstructured or dynamically changing environments.

Complementing this, the GPS module provides accurate geospatial positioning and long-range navigational support. It plays a pivotal role in route planning, path following on public roads, and reducing cumulative positioning errors during extended operation periods.

These two systems operate synergistically to enhance reliability and operational robustness. For example, in scenarios involving low visibility, such as during dusk, fog, or adverse weather, the visual system may degrade in performance—conditions under which GPS-based guidance can maintain navigational

accuracy. Conversely, in environments where satellite signals are obstructed or intermittent (e.g., near tree lines or in remote valleys), the visual system ensures continued trajectory control. Some implementations further integrate geomagnetic positioning sensors to enhance spatial localization, particularly in GPS-denied environments.

The strategic integration of these heterogeneous sensor systems significantly enhances the redundancy, adaptability, and precision of the vehicle's guidance framework. However, the increased complexity of these systems also introduces new challenges related to system maintenance, diagnostics, and lifecycle cost.

As agricultural machinery grows in sophistication, ensuring high reliability of the electronic and hydraulic subsystems becomes imperative. Unplanned equipment downtime due to failures in guidance or control systems can result in substantial financial losses, especially during time-critical harvesting operations. Therefore, improving system reliability—through both design robustness and intelligent maintenance strategies—represents a central focus in the evolution of automated field machinery.

While complexity in maintenance protocols may offer operational benefits by extending equipment lifespan and performance, it must be carefully managed. Excessive maintenance overhead or cost-ineffective solutions may undermine overall system viability. Consequently, a balanced approach that considers both technical performance and economic efficiency is essential for sustainable deployment of autonomous agricultural technologies.

RESULTS

In the development of complex agricultural systems, particularly autonomous or semi-autonomous combine harvesters, system designers must prioritize reliability, maintainability, and operational efficiency from the earliest design stages. A series of well-defined design principles can significantly reduce the probability of failure, simplify maintenance procedures, and enhance the long-term performance of the system. The following measures outline a comprehensive framework for reliability-oriented design:

1. **Minimization of System Complexity**

The initial design phase should aim to produce functional schematics that are as simple as possible, utilizing a minimal number of interdependent components. Unnecessary elements introduce additional failure points, increase the likelihood of malfunction, complicate maintenance, and elevate associated costs. Configurations that result in functional ambiguity or introduce unwarranted automation complexity should be eliminated at the conceptual stage.

2. Selection of High-Reliability Components

The choice of components with proven reliability is fundamental. Prioritizing parts with high mean time between failures (MTBF) contributes to stable system performance and reduces maintenance frequency. This facilitates predictive maintenance scheduling and supports cost-effective, long-duration operational cycles.

3. Strategic Placement of High-Failure-Probability Components

Components with a statistically higher likelihood of failure should be positioned in locations that ensure easy access for inspection and replacement. This approach avoids the need for partial or complete disassembly of complex assemblies, thereby minimizing service time and reducing equipment downtime.

4. Leak Prevention and Fluid Quality Management

Design solutions must address fluid containment, acoustic comfort, and environmental integrity. Key measures include the use of appropriately selected sealing elements (e.g., gaskets and O-rings) that are compatible with the system's working fluids and operational pressures. These solutions help prevent external leakage and maintain fluid quality over time.

5. Reduction of Energy Losses and Thermal Overload

To improve system efficiency and control operating costs, components and conduits should be dimensioned to minimize flow resistance. Increasing the nominal diameters of pipelines and hydraulic elements reduces pressure losses, mitigates overheating, and enhances overall energy efficiency.

6. Modular System Architecture

Adopting a modular design—where the system is composed of semi-independent subassemblies—improves fault tolerance and serviceability. In such architectures, localized failures (e.g., damage to a single seal) are less likely to cause systemic malfunctions, allowing for partial system functionality and isolated repairs.

7. Integration of Compact Functional Blocks

Where feasible, compact functional blocks should replace traditional interconnections made via pipes and mounting plates. This design practice reduces the number of joints and potential leakage points, improves structural compactness, and increases reliability by simplifying component integration and reducing service intervention complexity.

8. Preventive and Predictive Maintenance Planning

A robust preventive maintenance strategy must be embedded into the system from the design phase. This includes scheduling service intervals and specifying inspection procedures. Where applicable, the design should support integration with predictive or proactive maintenance tools, enabling early detection and mitigation of potential failures.

9. Provision of Diagnostic and Monitoring Access Points

Control points for measuring critical system parameters—such as flow rate, pressure, and temperature—should be included in the system layout. These diagnostic interfaces enable real-time monitoring and facilitate the integration of control equipment, ensuring consistent performance and simplifying troubleshooting during operation.

By incorporating these design strategies, engineers can significantly enhance the reliability, serviceability, and overall lifecycle performance of agricultural machinery systems, aligning technological advancement with practical field requirements.

CONCLUSIONS

The evolution of modern agricultural machinery, particularly combine harvesters, is increasingly defined by the integration of advanced automation, control systems, and reliability-centered design strategies. As these machines operate in complex, dynamic, and often unstructured field environments, their performance depends on the seamless coordination of hydraulic, mechanical, electrical, and electronic subsystems. Hydraulic systems, in particular, play a pivotal role in ensuring the synchronized operation of key components such as the reaper, cutting platform, variable speed drive, and steering mechanism.

The transition toward autonomous and semi-autonomous harvesting systems demands robust modeling, simulation, and control frameworks capable of capturing the multifaceted behavior of the machine and its interaction with varying crop and terrain conditions. Through hierarchical, modular simulation environments and real-time sensor integration—particularly GPS and camera-based navigation systems—harvesters are becoming increasingly capable of performing complex tasks with minimal human intervention while maintaining operational precision and safety.

At the core of these advances lies a deliberate focus on system reliability and maintainability. From simplifying functional schematics and selecting high-durability components, to designing modular architectures and embedding predictive maintenance capabilities, each design decision plays a critical role in reducing downtime, optimizing energy use, and minimizing the total cost of ownership. Complementary sensor fusion, preventive diagnostics, and real-time monitoring further contribute to enhancing both the performance and resilience of automated systems in the field.

Ultimately, the convergence of mechanical engineering, control theory, sensor technology, and agricultural science offers a powerful pathway toward the realization of highly efficient, intelligent, and autonomous harvesting platforms. As the agricultural sector continues to demand higher productivity, quality, and sustainability, these integrated engineering approaches provide the foundation for the next generation of self-propelled machines, enabling more informed, adaptable, and efficient field operations.

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ASSESSMENT OF AIRBORNE POLLUTION IN INDUSTRIAL CITIES OF THE DNIPROPETROVSK REGION AND PROSPECTS FOR THE CREATION OF GREEN PROTECTIVE BELTS

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ОЦІНКА ЗАБРУДНЕННЯ ПОВІТРЯ В ПРОМИСЛОВИХ МІСТАХ ДНІПРОПЕТРОВСЬКОЇ ОБЛАСТІ ТА ПЕРСПЕКТИВИ СТВОРЕННЯ ЗЕЛЕНИХ ЗАХИСНИХ СМУГ

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Keywords: *air borne pollution, nitrogen and sulfur dioxides, urban forest parks, protection strips*

ABSTRACT

The level of air pollution with PM 10 particles in two industrial cities exceeded the recommended annual concentration of PM10 up to 10-15 times. Pollution of the atmosphere of Dnipro city with sulfur dioxide is almost twice as high as the data for Kamyanske. The maximum permissible concentration of nitrogen dioxide in the air of Dnipro and Kam'yanske was exceeded by 1.5-3 times. The gradual replacement of the most vulnerable tree species with other, non-invasive and more resistant ones, for implementation in urban forest parks and shelterbelts is justified. *Phellodendron amurense, Eucommia ulmoides, Koelreuteria paniculata, Sorbus torminalis, Cladrastis kentukea, Gymnocladus dioicus* and some others, which are still rarely used, have great potential for urban park landscaping in steppe zone of Ukraine.

ТЕЗИ

Рівень забруднення повітря частинками PM10 у двох промислових містах перевищив рекомендовану річну концентрацію PM10 до 10-15 разів. Забруднення атмосфери міста Дніпро діоксидом сірки майже вдвічі перевищує дані для Кам'янського. Гранично допустима концентрація діоксиду азоту в повітрі Дніпра та Кам'янського була перевищена в 1,5-3 рази. Обгрунтована поступова заміна найбільш вразливих видів іншими неінвазивними та більш стійкими породами дерев для покращення міських парків та захисних лісосмуг. *Phellodendron amurense, Eucommia ulmoides, Koelreuteria paniculata, Sorbus torminalis, Cladrastis kentukea, Gymnocladus dioicus* і деякі інші, які поки що рідко використовуються, мають великий потенціал для міського озеленення в степовій зоні України.

INTRODUCTION

Constant exceeding of the MPC for the level of technogenic dust, nitrogen dioxide, sulfur and other pollutants in the atmosphere of urban agglomerations leads to the formation of acid rain, photochemical smog and an increase in the number of diseases among the local population *(Karnaukh and Lugovskoy, 2008; Stankevich et al., 2016; Kharytonov et al., 2017).*

It is known that the first metallurgical enterprises of the cities of Dnipro and Kamianske were built at the end of the 19th century on the banks of the Dnipro River in close proximity to the residential areas.

Therefore, at the end of the 20th century, the environmental situation in these cities deteriorated. The metallurgical plants located here have switched to modernization, replacement of equipment and technological processes only in the last two decades *(Babiy et al., 2003).*

The main task of solving the problem of reducing aero-technogenic pollution of industrial cities is to organize a network of posts for regional and local monitoring *(Kharytonov et al., 2015; Batur and Babii, 2022).*

The second task concerns the creation of a network of urban forest parks in residential areas, landscaping of enterprise territories and the creation of green belts from forest plantations around industrial agglomerations *(Khan and Abbasi, 2002).*

Tree plantings 30 m high ensure almost complete dust capture and a significant reduction in the concentration of gaseous pollutants In this regard, many studies are devoted to finding promising species for urban landscaping that are tolerant to the effects of pollutants. For example, experiments by Zhang et al. (2013) with fumigation chambers made it possible to assess the sensitivity of forest trees to air pollutants in subtropical climate. Two of the six species were selected after SO_2 fumigation to create green belts near industrial agglomerations *Ilex rotunda* remained green and absorbed the largest amount of SO_2, while *Cassia surattensis* can be used to improve the oxygen/carbon dioxide ratio in polluted areas.

Another study showed that deciduous trees are relatively sensitive to SO_2 during early growth and become more tolerant with age, while conifers are relatively tolerant during early growth and become very sensitive at peak wood growth, with this sensitivity persisting until early maturity *(Be and Baciak, 2015).*

The accumulation of various air emissions in areas with a high concentration of industrial facilities results in the appearance of more than one harmful substance, and the vegetation is constantly exposed to changing combinations of various toxic substances of varying concentrations *(Mohrena et al., 1992; Paoletti et al., 2010; Geiser et al., 2019).*

In this case the susceptibility of vegetation to damage in areas with exposure to many toxic substances became higher than in the presence of only one harmful substance. A floristic variety of native tree species in a steppe zone of southeast Ukraine is rather poor and totals no more than 40 species. And only some of them are used for urban forest establishment as many of natural species do not endure urbanistic pressure.

Therefore the overwhelming majority of urban forest species are introduced from other geographical areas. It was shown that planting fast growing tree species such as *R. pseudoacacia and A. platanoides* can be an environmentally appropriate and cost-effective measure to mitigate the toxic effects of heavy metals in the park areas *(Lovynska et al, 2024; Lakyda et al., 2025).* Unfortunately, global climate change and increasing anthropogenic pressure lead to destruction of urban ecosystem balance. It makes urban trees vulnerable to damaging by pests and pathogens, leads to life length reduction.

An example is leaf spot caused by the leaf miner Cameraria ohridella (*Lepidoptera, Gracillariidae*), which limits the use of *Aesculus* in urban landscaping *(Sytnyk et al., 2025).* Therefore new resistant trees without invasive risk can be studied and considered as alternative solution to introduction in urban forest assortment.

The main objective of this article was to estimate the man-made atmospheric pollution in industrial cities of the Dnipropetrovsk region and prospects for the creation of green protective belts.

MATERIALS AND METHODS

The tree plantings are natural barrier which protects atmosphere from harmful emissions. However natural woods in a steppe zone of Ukraine take up only 6 % of its territory. That's why artificially created forests carry out important water-retaining, phytomeliorative and recreational functions, increase biodiversity, and serve as reserves for valuable plant and animal species. However, today many of these ecosystems are in a destructive state. It is related both with anthropogenic influence and region environmental conditions. The climate of the southeast of Ukraine becomes more arid. Obvious insufficiency of water supply is observed. Total annual precipitation is small (400-500 mm) and varies significantly over the course of the warm season. Frequent droughts and high average daily temperatures of air during plant vegetation strengthen negative influence on artificial forest ecosystems. The assessment of air pollution was carried out in two urban cities: Dnipro and Kam'yanske, and was based on data from monitoring stations and the Earth Remote Sensing Center.

A review of tree species that are promising for urban park landscaping is based on many years of introduction research conducted in the Oles Honchar Dnipro National University Botanical Garden. It is located in the central part of the Dnipro city, occupies an area of 27 hectares, is one of the structural elements of the city wide greening system and along with other city forests is fully exposed to different stress factors.

RESULTS

The technogenic dust, dioxides of nitrogen and sulphur are main parameters connected with damage to forest trees. An average annual data on respirable particulate matters (PM) PM10, SO_2 and NO_2 observed for Dnipro and Kam'yanske cities are shown in the figure 1-3.

According to the World Health Organization's guidelines on air quality, the recommended annual concentration of PM10 should not exceed 0.02 mg/m^3 (World Health Organization 2005). The level of air pollution with PM 10 particles in two industrial cities was 10-15 times higher. Pollution of the atmosphere of Dnipro city with sulfur dioxide is almost twice as high as the data for Kam'yanske. However, excess of the maximum concentration was not recorded in the atmosphere of both cities. At the same time, the maximum permissible concentration of nitrogen dioxide in the air of Dnipro and Kam'yanske was exceeded by 1.5-3 times.

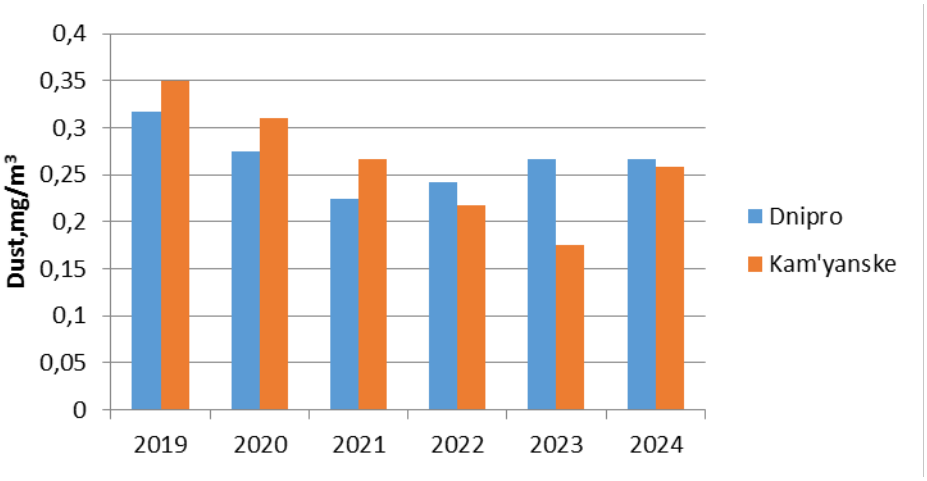

Fig. 1 - An average annual data on PM10 for two cities

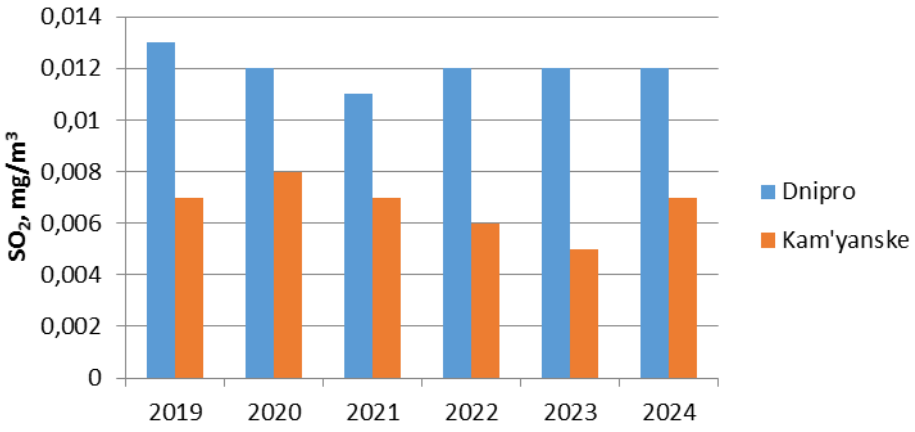

Fig. 2 - An average annual data on SO_2 for two cities

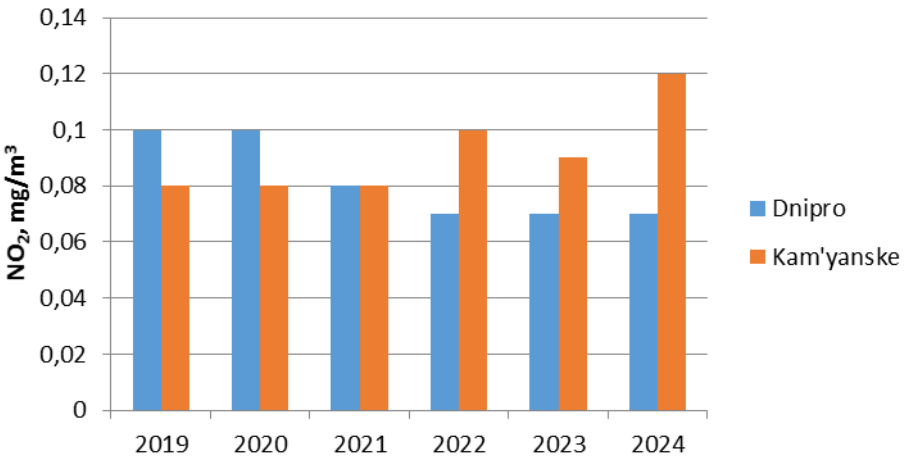

Fig. 3 - An average annual data on NO_2 for two cities

Based on the results of determining the content of nitrogen and sulfur dioxides in the atmosphere of the Dnipro and Kam'yanske cities, the method of overlaying maps was applied. It should be noted that nitrogen dioxide and sulfur dioxide have a summation effect. In the presence of many dispersed sources, individual emissions are superimposed and a total flare is formed, which spreads over industrial agglomerations.

As a result, maps of the risks of total man-made pollution of the atmosphere of two industrial agglomerations NO_2 and SO_2 were made (Fig. 4).

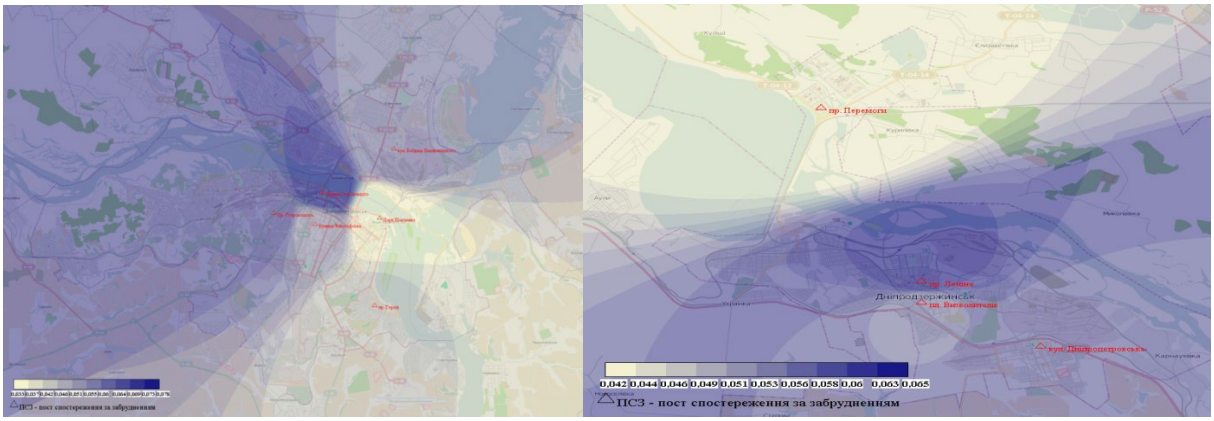

Fig. 4 - Maps of the cumulative assessment of atmospheric pollution risks in Dnipro (left) and Kam'anske (right) with nitrogen and sulfur dioxides

Analysis of maps of the distribution of NO_2 and SO_2 in the atmosphere of two cities in the Dnipropetrovsk province indicates the formation of certain aerosol circulation flows. It is obvious that the greatest attention to greening the territory of these two cities should be directed to the places of formation of smog of nitrogen and sulfur dioxides reflected on the prepared GIS maps.

The degree of damage to plants from the accumulation of toxic substances in them can vary greatly between individual species. Some of them are damaged by low accumulation of pollutants in the air of leaves, while others are damaged by their amount, which is 10-30 times higher *(Nowak et al., 2014; Sonwani et al., 2022)*.

In this regard, it is necessary to create protective green plantings from more resistant species; use gas-resistant plants with high gas-absorbing capacity as a natural filter; take into account the nature of pollution in a particular area when planting urban forest plantations.

Introduction of resistant plants in urban forest structure allows opening in full their ornamental features, to increase longevity and functionality. Today, the main problems of urban plantings are damage by pests and diseases, as well as a reduction of lifespan due to anthropogenic load. Monitoring of Dnipro city urban forests has shown that only 12 from 50 dominant species had no signs of any damages. Trees of *Aesculus hippocastanum* are often damaged by chestnut borer, *Ulmus sp.* by graphiosis, *Acer platanodes, Populus sp*. by tinder fungus.

Another problem of urban forests is the presence of adventitious species with a high potential for expansion and naturalization: *Acer negundo, Ulmus pumila, Robinia pseudoacacia, Celtis occidentalis, Ailanthus altissima* etc. These types of trees often spread from artificial plantings to local ecosystems, where they make serious competition to native species.

One of the methods for improving the state of urban forests may be the introduction and gradual replacement of the most vulnerable species by other more stable in the current conditions, and which do not have an invasive threat. Long-term monitoring of the woody plants collections in the DNU botanical garden allows us to pick out promising species for enriching the biodiversity in urban forests (table 1).

Table 1

Tree species that can be recommended for improving the state of urban forests in the steppe zone of Ukraine

Name	Origin	Height, category
Sorbus torminalis	indigenous	I
Carpinus betulus	indigenous	II
Acer campestre	indigenous	II
Catalpa speciosa	North America	II
Gymnocladus dioicus	North America	II

Cladrastis kentukea	North America	II
Juglans mandshurica	Far East Asian region	I
Phellodendron amurense	Far East Asian region	I, II
Eucommia ulmoides	Far East Asian region	II
Koelreuteria paniculata	Far East Asian region	II

The species presented in the table showed high resistance and viability in arid steppe conditions, as well as tolerance to anthropogenic pressure. Adding some exotic species (*Ginkgo biliba, Liriodendron tulipifera, Pseudotsuga mensiensii*) to the offered range can help enhance the ornamental effect of park plantings.

CONCLUSIONS

The territory of the industrial agglomerations in the Dnipropetrovsk region exposed to severe anthropogenic influence caused by intensive chemical, metallurgical and mining industries concentrated in the region. Constant excess of maximum permissible concentration level of technogenic dust, nitrogen and sulfur dioxides and other pollutants in atmosphere of urban agglomerations leads to formation of acid rains and a photochemical smog.

The total toxicity of these pollutants can be much more in consequence of summation effect. A floristic variety of tree species in a steppe zone of southeast Ukraine is rather poor and totals no more than 40 species. And only some of them are used for urban forest establishment as many of native species do not endure urbanity pressure. Therefore the overwhelming majority of urban forest species are introduced from other geographical areas.

Unfortunately, global climate change and increasing anthropogenic pressure lead to destruction of urban ecosystem balance. It makes urban trees vulnerable to damaging by pests and pathogens, leads to lifespan reduction. As alternative solution we consider introduction in urban forest assortment a few resistant tree species of North American and Asian origin, and three indigenous species as well.

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POTENTIAL AND PERSPECTIVES OF ORCHARD LIGNOCELLULOSIC BIOMASS AS A SOURCE OF RENEWABLE ENERGY IN THE REPUBLIC OF MOLDOVA

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POTENȚIALUL ȘI PERSPECTIVELE BIOMASEI LIGNOCELULOZICE POMICOLE CA SURSĂ DE ENERGIE REGENERABILĂ ÎN REPUBLICA MOLDOVA

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Keywords: *fruit tree biomass; pruning residues; solid biofuels; sustainable energy potential; calorific value; ash content; Republic of Moldova*

ABSTRACT

The utilization of residues resulting from orchard pruning represents a promising solution for diversifying renewable energy sources and reducing dependence on fossil fuels in the Republic of Moldova. This study assesses the availability, quality, and sustainable energy potential of lignocellulosic biomass from seed and stone fruit species cultivated in different economic regions, based on samples collected from orchards larger than 10 ha. The analyses included biomass yield, moisture content, net calorific value, and ash content. Results indicate high sustainable energy potential values for peach (33.50 ± 6.54) GJ/ha*, apple (29.67 ± 5.17)* GJ/ha*, and pear (29.45 ± 2.51)* GJ/ha*. The Northern region, dominated by apple orchards, accounts for the largest share of the national potential (467.73 – 665.13)* TJ/yr*, while the Central region stands out for plum and pear, and the Southern region for peach and apricot. Cherry residues show the lowest sustainable energy potential 17.61* GJ/ha *and the highest predictive uncertainty Up = 8.99* GJ/ha*. At the national level, the total sustainable energy potential is estimated between 806.50 and 1161.46* TJ/yr*, and the use of this biomass could substitute significant amounts of coal, natural gas, and fuel oil, reducing greenhouse gas emissions and supporting the transition to a sustainable energy system.*

REZUMAT

Valorificarea reziduurilor provenite din tăierile de întreținere ale plantațiilor pomicole constituie o soluție promițătoare pentru diversificarea surselor de energie regenerabilă și reducerea dependenței de combustibili fosili în Republica Moldova. Studiul evaluează disponibilitatea, calitatea și potențialul energetic sustenabil) al biomasei lignocelulozice de la specii sământoase și sâmburoase cultivate în diferite zone economice, pe baza probelor colectate din livezi de peste 10 ha. Analizele au vizat producția de biomasă, umiditatea, valoarea calorifică netă și conținutul de cenușă. Rezultatele indică valori ridicate ale potențialul energetic sustenabil pentru piersic (33.50 ± 6.54) GJ/ha*, măr (29.67 ± 5.17)* GJ/ha *și păr (29.45 ± 2.51)* GJ/ha*. Nordul țării, dominat de livezi de măr, deține cea mai mare pondere a potențialului național (467.73 – 665.13)* TJ/yr*, Centrul se remarcă prin prun și păr, iar Sudul prin piersic și cais. Cireșul prezintă cel mai redus potențialul energetic sustenabil 17.61* GJ/ha *și cea mai mare incertitudine Up = 8.99* GJ/ha*. La nivel național, potențialul energetic sustenabil total este estimat între 806.50 și 1161.46* TJ/yr*, iar utilizarea biomasei ar putea substitui combustibili fosili, reducând emisiile de gaze cu efect de seră și susținând tranziția spre un sistem energetic durabil.*

1. INTRODUCTION

Renewable energy plays a crucial role in the current context of the Republic of Moldova, a country that imports approximately 70% of its energy resources *(NBSRM., 2024, pp. 338 - 346)*. In this context, the identification and utilization of local renewable energy sources represent a strategic priority for ensuring energy security and sup-porting the transition towards a sustainable energy system. One of the most promising renewable sources in the Republic of Moldova is biomass, which can make a significant contribution to this transition.

To stimulate the use of biomass for energy purposes, the Republic of Moldova has adopted several policies and strategies aimed at promoting renewable energy sources. Among these are the Energy Strategy of the Republic of Moldova until 2030 *(GRM, 2013)* and the Energy Strategy of the Republic of Moldova until

2050 *(GRM, 2024*). These strategies pursue the development of a sustainable and competitive energy sector through market reforms and integration into the European Union's energy market.

The strategies target a series of objectives aimed at strengthening energy security, increasing the efficiency of energy resource use, and diversifying the energy mix, with a particular emphasis on promoting renewable energy and reducing dependence on imports, in the context of the transition towards a sustainable energy system and the commitments undertaken to combat climate change.

In parallel, the National Energy and Climate Plan 2025 – 2030 was developed by the Ministry of Energy, with support from the European Union provided through the program "Addressing the Impact of the Energy Crisis in the Republic of Moldova", implemented by UNDP Moldova *(GRM, 2025)*.

This plan sets out the priorities, objectives, and policies necessary to ensure a sustainable and affordable energy system for all consumers, while also defining the national targets in the fields of renewable energy, energy efficiency, and greenhouse gas emission reduction.

To achieve these objectives, the Government of the Republic of Moldova, in collaboration with international partners, has launched and implemented financial support programs focused on the development of biomass-fueled heating plants and the expansion of capacities for the production of densified solid biofuels, such as pellets and briquettes. Academic and research institutions in the Republic of Moldova are actively involved through research and innovation projects dedicated to the development of advanced technological solutions for the valorization of biomass resources. These efforts represent a key factor in promoting and consolidating the use of renewable energy sources derived from plant biomass, a locally abundant resource with low environmental impact.

Among plant biomass sources, those originating from the agricultural sector play a particularly important role *(Janiszewska & Ossowska, 2024)*. The use of agricultural residues as raw material for solid biofuel production contributes not only to reducing dependence on fossil energy resources and decarbonizing the energy sector, but also to supporting the transition towards sustainable production and consumption models, in line with the principles of the circular economy applied to the agri-food sector *(Ciloci & Țurcan, 2023; Silvestri et al., 2024)*.

Within this category of residues, orchard lignocellulosic biomass shows the greatest potential for use as feedstock in the production of densified solid biofuels *(Aliaño et al., 2022; Cavalaglio et al., 2024; Ciolacu et al., 2022; Marian & Banari, 2025).*

Orchard biomass comprises the totality of organic materials derived from fruit trees and shrubs, generated through orchard maintenance and exploitation activities. This includes residues from formative and maintenance pruning, annual fruiting cuts, tree thinning, the removal of dry or diseased branches, the clearing of trees at the end of their productive cycle, as well as soil cleaning and care operations.

From a compositional perspective, orchard biomass consists of wood, branches and twigs, leaves, bark, as well as other wastes resulting from the industrial processing of fruits *(Cavalaglio et al., 2024; Winzer et al., 2017)*. These residues are characterized by promising energy properties, which make them suitable for direct use in the production of pellets and briquettes, offering advantageous energy characteristics *(Alakangas, 2016; Marian et al., 2022).*

The present study aims to provide a detailed qualitative and quantitative analysis of plant biomass resources derived from fruit-growing in the Republic of Moldova, with a focus on their use for the production of densified solid biofuels. In this context, it is important to note that both the quantity and the quality of orchard biomass vary significantly depending on factors such as climatic conditions, harvesting time and method, geographical characteristics, moisture and mineral content, or conditioning methods *(Ibitoye et al., 2023)*. This variability is frequently highlighted in the specialized literature, underlining the need for detailed local analyses.

For example, researchers from the Czech Republic and Poland established that apple orchards planted at a density of 3.5 × 1.2 m generate approximately 6762 kg/ha of woody biomass (*Burg et al., 2017)*. Although the amount of biomass per tree is relatively low (2.84 kg/tree), the high overall value is explained by the high planting density per unit area. This highlights the essential role played by orchard density in maximizing the total biomass yield at the field level.

Furthermore, Polish researchers, based on an analysis of data reported by five different authors, found that the biomass potential harvested from one hectare of apple orchard varies significantly depending on tree age, year of cultivation, variety, and planting density, with values ranging between 1000 and 9800 kg/ha *(Dyjakon et al., 2016, tab.1)*.

According to the same authors, the theoretical energy potential of biomass derived from apple tree pruning in Poland is estimated at 12.52 PJ/yr, calculated for a total orchard area of 193.44 · 10^3 ha (*Dyjakon et al., 2016, tab.2)*.

A similar trend is observed in other fruit tree species. For instance, based on the analysis of biomass quantities obtained from pear pruning, Živković reported a significant variation among cultivars planted at the same density (500 trees/ha), with values ranging from 9.36 kg/tree (equivalent to 4680 kg/ha) for the 'Red-haven' cultivar to 4.85 kg/tree (2425 kg/ha) for the 'Summerset' cultivar *(Živković et al., 2013)*.

Significant amounts of woody biomass can also be recovered from orchard removal. In this regard, researchers in Germany estimated an annual biomass production potential of 10.6 Mg/ha *(Winzer et al., 2017)*. To determine the total area of cleared orchards, the authors applied a clearance coefficient of 0.05. It is noteworthy that some researchers employ conversion coefficients to estimate the biomass potential obtained from fruit tree maintenance works in relation to the total fruit yield. For example, *(Pence et al., 2024)* proposed such coefficients for several fruit species: apple – 0.19; pear – 0.22; apricot – 0.19; cherry – 0.19; peach – 0.50.

Gudîma also applied a unit conversion factor related to the mass of the main production *(Gudîma, 2017)*, using a coefficient of 0.28 for pome fruit trees and 0.26 for stone fruit trees. These coefficients were adjusted according to the availability of biomass for energy purposes and the inevitable losses occurring during its collection, transport, and processing. The author applied an availability coefficient of 0.8 and a loss coefficient of 0.9. Thus, the effective conversion coefficients, calculated for a biomass moisture content of 10%, were 0.202 and 0.187, respectively.

A similar methodology was adopted by Pavlenco, who provided detailed unit conversion factors for each species. For the pome group, the proposed values are: apple – 0.28 ± 0.02, pear – 0.20 ± 0.03, and quince – 0.14 ± 0.04; for the stone fruit group: sour cherry – 0.16 ± 0.02, sweet cherry – 0.24 ± 0.03, apricot – 0.26 ± 0.05, peach and plum – 0.26 ± 0.04 *(Pavlenco et al., 2018)*. Similarly, the authors applied an availability coefficient of 0.8 and a loss coefficient of 0.9.

The analysis of the data presented by the aforementioned authors highlights that the average production of woody mass resulting from fruit tree maintenance works varies significantly, being influenced by a range of objective and subjective factors. On average, these variations may reach values between 1.5 and 10 Mg/ha. In this context, knowledge of the average amount of biomass available, suitable for use as raw material in different regions of the country, is essential for substantiating decisions regarding the organization of solid biofuel production in specific localities.

At the same time, modern standards for solid biofuel quality (e.g., EN ISO 17225 series) require detailed knowledge of the physico-chemical properties of biomass, in order to ensure compliance with the accepted quality classes on both domestic and international markets. These requirements particularly refer to the calorific value and ash content, parameters strongly influenced by the origin of the biomass used as raw material for producing densified solid biofuels *(Toscano et al., 2023)*.

There are few studies dedicated to an integrated assessment of the sustainable energy potential (SEP), understood as the annual amount of energy obtainable from orchard biomass under real conditions of harvesting, processing, and utilization, in the Republic of Moldova, and the available data remain fragmented and uncorrelated with the geographical distribution of orchards as well as with the specific features of the country's economic development zones.

For instance, data published by Marian and Banari *(Marian & Banari, 2025)* refer to the energy potential of nut crop residues, expressed in GJ/ha, for three species—walnut, hazelnut, and almond—differentiated into two categories of biomass: woody biomass and endocarp. A more detailed evaluation of the energy potential of lignocellulosic biomass is presented for residues from vineyard plantations *(Marian et al., 2024)*.

However, there is a lack of well-substantiated data based on detailed studies concerning the energy potential of biomass derived from fruit tree plantations in the Republic of Moldova, as well as comparative analyses between different fruit species in terms of biomass productivity, calorific value, ash content, and estimation uncertainty.

In this context, the present study addresses an urgent need to substantiate, using experimental data and validated methodologies, the SEP of fruit-tree lignocellulosic biomass, differentiated by species and by regions. The results obtained can provide a scientific basis for the development of regional strategies for the collection, processing, and integration of orchard biomass into the national energy mix, thereby reducing dependence on fossil fuels and supporting decarbonization and circular economy objectives.

2. MATERIALS AND METHODS

2.1. Study area and sampling design

The research was conducted in the main fruit-growing regions of the Republic of Moldova: North, Center (including the municipality of Chișinău), and South (including the Autonomous Territorial Unit of Gagauzia). Orchards belonging to agricultural enterprises and family farms with areas larger than 10 ha were selected, as they are considered representative of the orchard structure in each region. The investigated species included fruit trees from the pome group (apple, pear, quince) and the stone fruit group (plum, cherry, sour cherry, apricot, peach), thus covering the typological diversity of orchards across the country.

The study focused on biomass generated from the annual maintenance and rejuvenation pruning of fruit trees. Samples were collected from representative plots, and the data were extrapolated to larger orchard areas. Tree sampling was carried out using the quarter method.

2.2. Biomass collection and measurement

Annual residues resulting from maintenance pruning were collected during the standard pruning period (February–March). For each orchard, tree density (number of trees/ha) and the average fresh biomass yield per tree were recorded. Moisture content at the time of collection was determined according to ISO 18134-2 by oven-drying the samples at 105 ± 2 °C until constant weight, with weighing differences ≤ 1 mg.

Based on these data, biomass yield per hectare and dry matter yield at the standard 10% moisture content were calculated.

2.3. Biomass characterization

Subsamples of each biomass type were analyzed to determine the net calorific value (NCV) at 10% moisture content, based on the gross calorific value (GCV) measured with an IKA C6000 isoperibolic bomb calorimeter, under constant volume conditions, according to ISO 18125:2017. The ash content (A, % dry basis) was determined according to ISO 18122:2015.

For comparative analysis among species, weighted averages were calculated according to the share of each species in the total orchard area.

2.4. Estimation of the sustainable energy potential

The SEP was calculated by correcting the theoretical energy potential (TEP) with factors reflecting technical losses, logistical constraints, and ecological limitations, according to the following equation:

$$SEP = TEP \cdot A_i \cdot (1-k_{il}) \quad (1)$$

where:

TEP represents the theoretical energy potential, calculated as the product between the biomass yield per hectare (dry basis at 10% moisture content) and the net calorific value of the biomass (determined at 10% moisture and constant pressure); A_i – is the availability coefficient of biomass for energy use; k_{il} - the implementation loss coefficient.

The total SEP values [TJ/yr] at regional and national levels were obtained by multiplying SEP values per hectare by the cultivated areas of each species, according to official data from the National Bureau of Statistics of the Republic of Moldova. Minimum and maximum SEP estimates were derived from the variability of field-measured biomass yields.

3. RESULTS

3.1. Assessment of the availability of orchard biomass for densified solid biofuel production

Table 1 presents the estimated amounts of biomass obtained from pome fruit plantations. The study included apple, pear, and quince varieties, which are widely cultivated in the Republic of Moldova. Samples were collected from traditional, semi-intensive, and intensive orchards, following the methodology described in Section 2.

The data show that the analyzed apple varieties vary considerably in terms of biomass generated per tree, with values ranging from 2.67 kg/tree (Fuji) to 6.23 kg/tree (Florina). A similar pattern was observed for pears, where values range from 1.21 kg/tree (Celina) to 5.27 kg/tree (Conference). These differences can be explained primarily by plantation density as well as orchard management and regeneration practices. Generally, trees from intensive orchards generate smaller amounts of biomass per tree, while more vigorous varieties grown at moderate densities (e.g., Florina, Golden, Reinette Simirenko) appear to be the most energy-efficient.

Table 1

Average biomass yield, calorific value, and ash content from pruning of pome fruit species

Species	Type	n_{th}*	m_t	M_h	m_h	$m_{M=10\%}$	$q_{Pnet\ M=10\%}$	A	$m_{sp\ M-10\%}$	$q_{sp\ Pnet\ M=10\%}$	A_{sp}
Apple	Idared	1250	2.84	43.17	3550.00	2241.63	15.58	3.93	2639 ± 456	15.61 ± 0.33	3.03±0.61
	Idared	833	5.48	42.15	4564.84	2934.18	15.63	3.82			
	Reinette Simirenko	1250	3.06	43.59	3825.00	2397.43	15.76	4.11			
	Reinette Simirenko	833	6.03	42.73	5022.99	3196.30	15.76	4.15			
	Florina	833	6.23	43.97	5189.59	3230.81	15.67	2.21			
	Golden Delicious	833	5.68	42.42	4731.44	3027.07	15.97	2.82			
	Gala	1250	3.12	43.21	3900.00	2460.90	14.93	2.96			
	Fuji	1250	2.67	43.11	3337.50	2109.67	15.58	1.96			
	Jonathan	570	5.97	43.11	3402.90	2151.01	15.63	3.16			
Pear	Conference	833	5.27	45.58	4389.91	2654.43	15.89	3.55	2620 ± 212	15.58 ± 0.41	3.35±0.31
	Noyabrskaya (Xenia)	1428	3.33	47.77	4755.24	2759.62	15.63	3.24			
	Celina	2800	1.24	42.24	3472.00	2228.25	15.57	3.27			
	Doyenné d'Hiver	833	5.21	47.28	4339.93	2542.23	16.00	3.35			
	Passe Crassane	1250	3.75	47.46	4687.50	2736.46	15.57	2.89			
	Clapp's Favourite	1428	3.10	43.12	4426.80	2797.74	14.82	3.81			
Quince	Auriu	800	3.21	43.21	2568.00	1620.41	15.39	3.49	1338±215	15.37±0.37	3.46±0.06
	Yantarnaya Moldavii	834	2.14	42.98	1784.76	1130.74	15.37	3.36			
	Zarea	800	3.04	44.21	2432.00	1507.57	15.74	3.47			
	Cometa	800	2.32	43.11	1856.00	1173.20	15.61	3.53			
	Olga	800	2.45	42.14	1960.00	1260.06	14.76	3.46			

**n_{th} – Number of trees per hectare* [trees/ha]*; m_t – Average biomass yield per tree* [kg/tree]*; M_h – Moisture content of the biomass at harvest, percent wet basis* [$\%_W$]*; m_h – Average biomass yield per hectare at harvest* [kg/ha]*; $m_{M=10\%}$ – Average biomass yield per hectare calculated to 10% moisture* [kg/ha]*; $q_{PnetM=10\%}$ - Net calorific value at constant pressure, calculated for 10% moisture content* [MJ/kg]*; A - Ash content on a dry basis* [%]*;$m_{spM=10\%}$ – Average biomass yield per species calculated to 10% moisture* [kg/ha]*; $q_{spPnetM=10\%}$ - Species average of the net calorific value at constant pressure, calculated for 10% moisture content* [MJ/kg]*;A_{sp} – Average ash content on a dry basis* [%]

At the area level, pear orchards produce on average similar amounts of biomass as apple orchards. Thus, the average usable biomass yield, adjusted to a 10% moisture content, is 2620 ± 212 kg/ha for pear and 2639 ± 456 kg/ha for apple. Quince, by contrast, generates a significantly smaller amount of biomass compared with the other two species. The mean quantity per tree is only 2.63 kg, while at the hectare level the average yield is 1339 ± 215 kg/ha, estimated at 10% moisture content. The moisture content of the biomass, determined immediately after collection, did not vary significantly among the analyzed species, averaging around 44%. This highlights the need for pre-conditioning of the biomass through drying before its energetic utilization.

Among the analyzed species, apple and pear provide the highest potential for the production of densified solid biomass (briquettes, pellets), with comparable average yields of around 2,600–2,700 kg/ha (at 10% moisture content). Therefore, it is recommended to correlate biomass productivity data with economic and ecological factors in order to enable an optimal selection of cultivars for energy purposes, also taking into account the specific calorific value of biomass from different fruit tree species.

It was found that the calorific value of biomass obtained from the 9 samples of different apple cultivars, 6 of pear, and 5 of quince did not differ significantly between the fruit tree species.

Based on the average values determined for each fruit tree cultivar, the mean value for the entire group of pome fruit trees was calculated. The analysis of the results indicates that biomass at 10% moisture content presents an average net calorific value of 15.61 ± 0.33 MJ/kg for apple, 15.58 ± 0.41 MJ/kg for pear, and 15.37 ± 0.37 MJ/kg for quince.

These values highlight only a minor variation between the analyzed species, the difference being about 0.24 MJ/kg, while the overall mean for the pome group is 15.52 MJ/kg.

With reference to the requirements specified in the SM EN ISO 17225 standards, it can be stated that the woody residues from fruit trees of the pome group are suitable for briquette production, fitting into

quality classes A1, A2, and B in terms of calorific value. However, the use of these residues is restricted by the relatively high ash content, which exceeds the 3% threshold. In this context, the analyzed biomass is more suitable for the production of B-class wood briquettes, meeting the criteria related to calorific value and ash content.

The physico-mechanical parameters of the final product are essentially influenced by the technology applied in the biofuel production process. In addition, this raw material has high potential for the manufacture of pellets and briquettes from non-woody biomass, including in mixtures (blends), thus expanding the possibilities of energy valorization.

Table 2 presents the characteristics of biomass from stone fruit trees, collected in March. Peach generated the highest amount of biomass ($m_{spM=10\%}$ = 2909 ± 564 kg/ha), followed by plum ($m_{spM=10\%}$ = 1980 ± 246 kg/ha) and sour cherry ($m_{spM=10\%}$ = 1854 ± 246 kg/ha), while apricot recorded the lowest value ($m_{spM=10\%}$ = 1504 ± 130 kg/ha).

Table 2

Average biomass yield, calorific value, and ash content from pruning of various stone fruit spe-cies

Species	Type	n_{th}*	m_t	M_h	m_h	$m_{M=10\%}$	$q_{Pnet\ M=10\%}$	A	$m_{sp\ M-10\%}$	$q_{sp\ Pnet\ M=10\%}$	A_{sp}
Plum	Stanley	444	7.81	47.01	3467.64	2041.67	16.21	1,7	1981 ± 246	16.21 ± 0.52	2,06 ± 0.20
	Valor	889	4.21	48.12	3742.69	2157.45	15.61	2,19			
	President	800	3.28	47.17	2624.00	1540.29	16.47	2,24			
	Ana Spath	1000	3.77	47.97	3770.00	2179.48	16.95	2,16			
	Piteştean	800	3.82	45.44	3056.00	1852.62	15.63	2,06			
	Renclod Althan	667	5.32	46.38	3548.44	2114.08	16.41	1,99			
Cherry	Kordia	333	5.91	45.58	1968.03	1190.00	15.75	2,64	1566 ± 798	15.78 ± 0.51	2.65 ± 0.31
	Regina	833	3.94	47.77	3282.02	1904.67	15.85	3,04			
	Grace Star	330	6.02	46.21	1986.60	1187.32	15.61	2,29			
	Ferrovia	330	4.02	44.79	1326.60	813.80	15.08	3,02			
	Sweet Heart	830	6.23	47.32	5170.90	3026.70	16.65	2,41			
	Bigarreau Burlat	330	6.23	44.16	2055.90	1275.57	15.77	2,52			
Sour Cherry	Oblačinska	404	7.03	48.01	2840.12	1640.64	15.56	2,61	1854 ± 289	15.58 ± 0.45	2.81 ± 0.20
	Morella	500	6.53	43.91	3265.00	2034.82	16.16	2,58			
	Crișana	833	4.23	46.18	3523.59	2107.11	15.74	2,87			
	Nordh Star	833	4.01	45.23	3340.33	2032.78	15.52	3,03			
	Mărioara	404	6.43	49.62	2597.72	1454.15	14.91	2,96			
Apricot	Kyoto	500	5.12	41.89	2560.00	1652.91	15.9	3,91	1504 ± 130	15.87 ± 0.40	2.70 ± 0.68
	Krasnoshchyokiy	280	7.98	47.77	2234.40	1296.70	15.57	2,45			
	Platimoon	500	5.37	48.28	2685.00	1542.98	16.53	2,28			
	Orange Rubis	330	7.21	42.24	2379.30	1526.98	15.58	2,38			
	Big Red	502	5.13	47.53	2575.26	1501.38	15.79	2,49			
Peach	Cardinal	500	7.74	44.55	3870.00	2384.35	15.97	2,44	2909 ± 564	16.00 ± 0.36	1.90 ± 0.47
	Maycrest	1250	4.94	47.21	6175.00	3621.98	16.6	1,34			
	Moldova	500	7.42	42.24	3710.00	2381.00	15.76	1,57			
	Redhaven	1200	4.04	47.98	4848.00	2802.14	15.97	1,85			
	Stark Sunglo	1250	4.62	47.74	5775.00	3353.35	15.69	2,32			

Moisture content at harvest varied insignificantly among species, while the net calorific values (at 10% moisture) were similar: highest for plum (16.21 ± 0.52 MJ/kg) and lowest for sour cherry (15.58 ± 0.39 MJ/kg), with a difference of 0.63 MJ/kg. Ash content ranged from 1.90 ± 0.41% (peach) to 2.81 ± 0.18% (sour cherry).

The results confirm the literature *(Burg et al., 2017; Matłok et al., 2024)*, according to which stone fruit biomass, although having lower density, exhibits a calorific value comparable to other species, a fact correlated with lignin content: 23.31 ± 2.21% for peach and 24.26 ± 1.25% for plum *(Burg et al., 2017; Matłok et al., 2024)*.

3.2. Energy potential of available orchard biomass for solid biofuel production in different regions of the Republic of Moldova

The Republic of Moldova has 85.6 thousand hectares of orchards (pome and stone fruits), including 38.4 thousand hectares of plantations larger than 10 ha *(NBSRM, 2025)* with specific concentrations across Economic Development Zones:

- Northern Zone – districts such as Edineț, Briceni, Dondușeni, Soroca, Florești (mainly apple, plum, and cherry);
- Central Zone – districts such as Orhei, Hâncești, Strășeni, Călărași, Ialoveni (apple, plum, apricot, cherry);
- Southern Zone – districts such as Cimișlia, Cahul, Taraclia, Ștefan Vodă (peach, apricot, sour cherry).

The species structure directly influences the quantity and quality of biomass obtained from orchard maintenance. Table 3 presents the results of estimating the energy potential of biomass generated from different fruit tree species, distributed by the Economic Development Zones of the Republic of Moldova. The calculations were based on the experimental data presented in subsection 3.1.

Table 3

Energy potential of fruit tree pruning residues

Parameters		Pome fruit			Stone fruit				
		Apple	Pear	Quince	Plum	Sweet cherry	Sour cherry	Apricot	Peach
$m_{b\ M=10\%}$* [kg/ha]	$\bar{m}$	2639	2620	1338	1981	1566	1854	1504	2909
	σ	456	212	215	246	798	289	130	564
$q_{Pnet\ M=10\%}$ [MJ/kg]	$\bar{m}$	15.615	15.579	15.372	16.211	15.784	15.578	15.873	15.995
	σ	0.329	0.414	0.374	0.519	0.506	0.449	0.396	0.360
A_i		0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8
k_{il}		0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1
TEP [GJ/ha]		41.21	40.91	20.90	30.93	24.46	28.95	23.49	46.53
Up [GJ/ha]		7.19	3.49	3.40	3.99	12.49	4.59	2.12	9.08
PED [GJ/ha]		32.97	32.73	16.72	24.75	19.57	23.16	18.79	37.22
Up [GJ/ha]		5.75	2.79	2.72	3.19	9.99	3.67	1.69	7.27
SEP [GJ/ha]		29.67	29.45	15.05	22.27	17.61	20.84	16.91	33.50
Up [GJ/ha]		5.17	2.51	2.45	2.87	8.99	3.30	1.52	6.54

**$m_{bM=10\%}$ - average biomass yield converted to a moisture content of 10%; $q_{Pnet\ M-10\%}$ - net calorific value of biomass at 10% moisture content, calculated at constant pressure; TEP - theoretical energy potential; PED - available energy potential; SEP - sustainable energy potential; A_i – availability coefficient, equal to 0.8; k_{il} - implementation loss coefficient, equal to 0.1; Up – predictive uncertainty; m – mean value, σ – standard deviation.*

It was found that residues from peach, apple, and pear pruning exhibit the highest exploitable energy potential and are the most suitable species for energy valorization among the analyzed orchard residues. The exploitable energy — considering the efficiency of technological processes and the sustainability of biomass harvesting — is estimated at 33.50 ± 6.54 GJ/ha for peach, 29.67 ± 5.17 GJ/ha for apple, and 29.45 ± 2.51 GJ/ha for pear.

It is noteworthy that although cherry residues show a lower SESP index, they exhibit the highest predictive uncertainty (Up = 8.99 GJ/ha), which indicates significant variability of the data, most likely due to differences between species, planting schemes, pruning methods, growth conditions, and sampling locations.

The lowest values were recorded for quince (15.05 ± 2.45 GJ/ha), apricot (16.91 ± 1.52 GJ/ha), and cherry (17.71 ± 8.99 GJ/ha), which also had lower uncertainties in estimation.

This suggests a higher probability of obtaining more constant quantities of biomass from these plantations. At the same time, these species show favorable calorific values, indicating that they should not be neglected as raw material for solid biofuel production. The correlation between uncertainty and energy potential shows that species with higher yields also exhibit greater variations in the estimates, which requires more precise assessments at the level of specific orchards and localities before initiating the production of densified solid biofuels from these pruning residues. The analysis of the SEP of biomass derived from fruit trees in the Republic of Moldova (Table 4) highlights significant differences in SEP between economic development zones (Northern Zone, Central Zone including Chișinău municipality, and Southern Zone including ATU Gagauzia), as well as among the fruit species.

Table 4

Sustainable energy potential of fruit tree biomass from orchards belonging to agricultural enterprises and household farms in the Republic of Moldova, by region

Fruit tree species	Northern Zone			Central Zone + Chișinău Municipality			Southern Zone + ATU Gagauzia			National total	
	St* [ha]	SEP [TJ/yr]		St [ha]	SEP [TJ/yr]		St [ha]	SEP [TJ/yr]		SEP [TJ/yr]	
		max	min		max	min		[ha]	max	min	[ha]
Apple	13787	480.34	337.78	3302	115.04	80.90	2002	69.75	49.05	665.13	467.73
Pear	64	2.05	1.72	269	8.60	7.25	35	1.12	0.94	11.76	9.91
Quince	7	0.12	0.09	21	0.37	0.26	28	0.49	0.35	0.98	0.71
Plum	2365	59.46	45.88	5311	133.52	103.03	2634	66.22	51.10	259.19	200.01
Chery	1370	36.44	11.81	1492	39.69	12.86	502	13.35	4.33	89.48	29.00
Sour Cherry	542	13.08	9.51	856	20.66	15.01	593	14.32	10.40	48.06	34.92
Apricot	459	8.46	7.06	966	17.80	14.87	502	9.25	7.73	35.51	29.66
Peach	70	2.80	1.89	352	14.09	9.49	860	34.43	23.19	51.33	34.56
National total										***1161.46***	***806.50***

** St - total orchard area at agricultural enterprises and household farms with agricultural land holdings of 10 hectares and above.*

The total cultivated area with apple orchards is dominant in the Northern Zone (13787 ha), generating an annual SEP estimated between 337.78 and 480.34 TJ, followed by the Central Zone (3302 ha; 80.90 – 115.04 TJ/yr) and the Southern Zone (2002 ha; 49.05 – 69.75 TJ/yr). In total, the SEP of apple orchards available at agricultural enterprises and household farms in the Republic of Moldova ranges between 467.73 and 665.13 TJ/yr at the national level. For other species, such as pear, plum, and cherry, the energy potential varies according to cultivated area and local conditions, but it is noteworthy that orchards in the Central Zone generally generate higher values compared to the other regions.

For example, in the case of plum, the SEP varies between 45.88 – 59.46 TJ/yr in the North, 103.03 – 133.52 TJ/yr in the Center, and 51.10–66.22 TJ/yr in the South, summing up to a national potential between 200.01 and 259.19 TJ/yr. Overall, the orchard biomass from all the studied species provides an energy potential estimated at approximately 806.50 to 1161.46 TJ/yr for the entire country. This renewable resource can substantially contribute to the diversification of the energy mix and to the reduction of dependency on fossil fuels. Harnessing this potential would result in significant savings of fossil resources such as coal, oil, and natural gas, currently used for thermal and electrical energy generation. In addition, the integration of orchard biomass into the national energy mix supports sustainable strategies, contributing to greenhouse gas emission reductions and environmental protection.

To maximize the positive impact, detailed regional planning is required, considering the specific features of each zone, in order to ensure sustainable harvesting and efficient utilization of orchard biomass for the production of densified solid biofuels.

CONCLUSIONS

The results obtained in this study indicate that pruning residues from peach, apple, and pear orchards exhibit the highest SEP among the analyzed species, with values of 33.50 ± 6.54 GJ/ha for peach, 29.67 ± 5.17 GJ/ha for apple, and 29.45 ± 2.51 GJ/ha for pear. These findings are consistent with research carried out in Central and Eastern Europe (*Burg et al., 2017; Dyjakon et al., 2016)*, where pome and stone fruit species have been identified as promising feedstocks for solid biofuel production.

The regional distribution of biomass potential highlights clear differences determined by orchard structure and agroclimatic conditions. The Northern Zone, dominated by apple orchards, accounts for the largest share of the national potential, while the Central Zone stands out with higher values for plum and pear, and the Southern Zone for peach and apricot.

These results emphasize the need for adopting region-specific strategies for biomass collection and utilization, in order to optimize logistics and processing capacities. Although cherry residues show a lower SEP (17.61 GJ/ha), they also recorded the highest predictive uncertainty (Up = 8.99 GJ/ha). This high

variability is influenced by the biological characteristics of the species, planting schemes, and pruning practices, which necessitate additional monitoring and standardization of maintenance operations. From a practical perspective, the sustainable use of this biomass could substitute significant amounts of fossil fuels—particularly coal, natural gas, and fuel oil—currently employed for heat generation.

Depending on calorific values and available quantities, replacing fossil fuels with orchard biomass would directly contribute to reducing national greenhouse gas emissions and to fulfilling the Republic of Moldova's commitments under the European Green Deal. However, certain constraints must be considered.

The relatively high ash content (> 3% for some species) may limit direct use for premium-quality briquette and pellet production, requiring either blending with low-ash feedstocks or adapting combustion systems. Furthermore, the moisture content of biomass at harvest (~44–48%) necessitates a drying stage, which increases processing costs and affects the overall energy efficiency.

Future research directions should include:

- the development of logistic models for biomass collection adapted to the regional distribution of orchards;
- techno-economic analyses of integrated pellet and briquette production chains;
- life cycle assessments to quantify the environmental benefits resulting from large-scale substitution of fossil fuels with pruning residues from fruit orchards.

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METHODS OF OBTAINING BIOCHAR
/
METODE DE OBȚINERE A BIOCHARULUI

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ABSTRACT

In recent decades, biochar has attracted attention in both the political and academic spheres because it is easy to obtain and is beneficial for the environment. It can be used for soil stabilization, wastewater treatment, greenhouse gas management, in climate change mitigation strategies, and power generation. Biochar is the result of the thermochemical transformation of biomass. Its yield and quality are very different depending on the production technology and process parameters. They also have an impact on its performance in agricultural and forestry systems but also in other areas where it is used. This review compared different technologies for biochar production, such as slow pyrolysis, rapid pyrolysis, gasification, and roasting.

REZUMAT

În ultimele decenii biocharul a atras atenția atât în sfera politică, cât și în cea academică pentru că este ușor de obținut și este benefic pentru mediu. Poate fi folosit pentru stabilizarea solului, tratarea apelor uzate, gestionarea gazelor cu efect de seră, în strategiile de atenuare a schimbărilor climatice, și generarea de energie. Biocharul este rezultatul transformării termochimice a biomasei. Randamentul și calitatea sa sunt foarte diferite în funcție de tehnologia de producție și de parametrii de proces; acestea au, de asemenea, un impact asupra performanței sale în sistemele agricole și forestiere dar și în alte domenii în care este utilizat. Această revizuire a comparat diferite tehnologii pentru producția de biochar, cum ar fi piroliza lentă, piroliza rapidă, gazeificarea și torrefacția.

INTRODUCTION

Biochar is produced by the thermal breakdown of plant or animal biomass that is thermally decomposed in the absence of oxygen. It is a porous, aromatic and decay-resistant carbonic solid material. It has gained significant interest in recent years as it is used in a wide range of agricultural and industrial operations *(Rangabhashiyam and Balasubramanian 2019).*

Plant waste, manure, agricultural and forestry by-products, sludge, waste from paper mills, etc., can be used in the production of biochar *(Saletnik et al, 2019; Cobos-Torres et al, 2025; Su et al, 2025*). Biochar, or charcoal, is a sustainable solution for agriculture and the environment, which saw a surge in research in the 1990s.

Researchers investigated how biochar can improve soil quality while reducing greenhouse gas emissions. Since then, interest in biochar has grown, and research into its manufacture is constantly expanding.

Biochar is currently used to improve soil, produce energy, and capture carbon from the atmosphere. It is also a viable alternative to chemical fertilizers. *(Shyam et al, 2025; Kabir et al, 2023; Luo et al, 2023; Amalina et al, 2022; Allohverdi et al, 2021; Weber and Quicker 2018)*.

Biochar is mainly used to improve agricultural soil, improve the environment, and as part of several industrial applications. It improves soil fertility, improves water retention, and may help sequester carbon, which contributes to climate change mitigation *(Ayaz et al, 2025; Xiong et al, 2025).*

Biochar also has the ability to filter liquids and gases, remove pollutants, and be incorporated into textiles and other products *(Yaashikaa et al, 2020; Montanarella et al, 2013; Dong et al, 2025).*

The main areas in which biochar is used are:

1. **Improvement of agricultural soil** by:
   - ***Higher yields***. Biochar increases crop yields by improving soil structure, water-holding capacity, and nutrient availability *(Mak-Mensah, et al, 2021; Feng, et al, 2023; Hussain. et al, 2020)*
   - ***Soil health***. It can improve overall soil health by increasing soil aeration, reducing nutrient leaching, reducing soil acidity, soil decontamination *(Luo et al, 2021; Wei et al, 2019).*
   - ***Carbon sequestration***. The stable carbon content of biochar can remain in the soil for a long time. This makes it a carbon sink and helps reduce the effects of climate change *(Osman et al, 2024; Jafri et al, 2018)*.

2. **Remediating the environment means eliminating pollutants:**
   - ***Removal of pollutants***. Biochar has the ability to extract heavy metals, pesticides, organic and inorganic contaminants from soil and water.
   - ***Wastewater and water management***. It can be used as a filter to remove impurities and pollutants from water sources.
   - ***Odor management***. Biochar is useful in wastewater treatment and waste management because it can absorb odor-causing substances *(Murray 2021; Farah et al, 2022; Amalina et al, 2022)*.

3. **Industrial Applications**:
   - ***Textile:*** Biochar can be used in underwear fabrics that provide thermal insulation and reduce odors *(Schmidt 2012).*
   - ***Materials used in construction***: Potentially, biochar can be added to building materials to improve insulation and reduce the carbon footprint.
   - ***Energy production***: Biochar can be used as a fuel or as a catalyst in a variety of industrial processes *(Yaashikaa et al, 2020; Curcio et al, 2025).*
   - ***Materials required for electrodes***: Biocarbon can be used in supercapacitors and batteries *(Novak 2019).*
   - ***Adsorbent***: Biochar is good for adsorption of pollutants, gases, and other substances due to its large surface area and porosity *(Yaashikaa et al, 2020).*

4. ***In animal management***,
   - ***Animal health.*** Biochar is added to feed to improve animal health and reduce the amount of methane in manure *(Schmidt et al, 2019; O'Toole et al, 2016).*
   - ***Livestock***. Animals are healthier and agriculture more sustainable thanks to the detoxification of the digestive system *(www.causeartist.com)*

Although initially biochar was mainly used in agriculture, currently its use has expanded to a wide range of fields due to its properties, apart from those listed above, biochar is also used in the food industry, as a dye or in the manufacture of packaging, in the pharmaceutical and cosmetic industries in the manufacture of creams, soaps and deodorants *(Lin and Chang 2008).* Figure 1 shows a picture of the main uses of biochar.

Fig. 1 - Main uses of biochar
(www.biochar-industry.com)

The production of biochar is usually achieved through a series of thermochemical conversion processes, which are carried out under different process conditions. The four main processes of obtaining biochar are torification, gasification, slow pyrolysis, and rapid pyrolysis *(Leng et al, 2019; Adeniyi et al, 2024)*.

In addition to slow and fast pyrolysis that are most used, there are several types of pyrolysis, namely: microwave pyrolysis, hydropyrolysis, vacuum pyrolysis, flesh pyrolysis, copirolyrolysis, and intermediate pyrolysis *(Dilipkumar et al, 2021; Kwaku et al, 2023; Ahmed et al, 2025)*.

METHODS OF OBTAINING BIOCHAR

1. Pyrolysis

Pyrolysis is a thermochemical method that creates biochar, biooil, and syngas from biomass *(Bridgwater et al, 2000).* The process involves heating and thermally decomposing biomass under anaerobic conditions or with a limited oxygen supply, known as a low-oxygen stoichiometric atmosphere. Process temperatures range from 400°C to 1200°C (*Amin et al, 2016).*

1.1 Slow pyrolysis: As the name suggests, the slow pyrolysis process requires a long residence time (more than 1 hour), and the end result is biochar (*Liu et al, 2015).* Slow pyrolysis, also known as conventional pyrolysis, involves heating the biomass to 300–600°C and a heating rate of 5–7°C/min *(Li et al, 2020).*

1.2. Rapid pyrolysis: It is a direct thermochemical process that produces high-energy liquid bio-oil from solid biomass. a highly efficient thermochemical method that uses biomass to produce biofuels with reduced amounts of gases and solids produced *(Dai et al, 2017; Chang et al, 2021).* Without oxygen, rapid pyrolysis is carried out at temperatures above 500°C and heating rates of over 300°C/min. A rapid method of obtaining biochar is rapid pyrolysis, which takes only a few seconds. According to other studies, rapid pyrolysis creates 20% biochar, 60% biooil, and 20% syngas *(Dai et al, 2017; Huang et al, 2016).*

1.3 Microwave Pyrolysis: Microwave pyrolysis uses microwave radiation to heat materials, converting electromagnetic energy into heat during this process. The constant heating speed, along with cost efficiency, easy control, and safety features, have made microwave pyrolysis a viable option compared to traditional pyrolysis. A microwave oven is used to carry out this process. Two key factors for this method are power output and frequency. The standard frequency used in this process is 2.45 GHz. The temperature at which the process takes place varies between 400 and 600 °C *(Omoriyekomwan et al, 2017).*

Following the use of microwave pyrolysis to obtain biochar, the carbon content was 77.8% *(Kostas et al, 2020)*. Although the yield increases with temperature, the yield obtained from the use of microwave pyrolysis has been found to be lower than with the use of conventional pyrolysis *(Omoriyekomwan et al, 2017).*

1.4 Vacuum Pyrolysis: This method involves the decomposition of biomass by a thermal process in an oxygen-free environment, either under vacuum or under a fairly low pressure *(Lam.et al.2019).* Usually, the pressure is set between 0.5 and 2 bar, and the temperature is kept between 450 and 600 °C *(Carrier et al, 2011)*. Just like in slow pyrolysis, vacuum pyrolysis has lower heating speeds. However, these two methods generate very different products.

The reason is that the vapors created during vacuum pyrolysis are constantly and efficiently removed through a condensing system. The rapid removal of organic vapors produced in the main pyrolysis phase significantly reduces the time they remain, which helps to decrease side reactions and ensures a good percentage of liquid product during the pyrolysis secondary phase. For this reason, the vacuum or low-pressure extraction technique is exclusively used to remove the vapors released during pyrolysis, which greatly influences the quality and quantity of the product by preventing the release of inorganic substances *(Chen et al, 2017)*.

The carbon content remains low throughout this process, compared to standard pyrolysis, due to the intense reactions that take place in a vacuum. Increasing the temperature reduces the amount obtained, while increasing the size of the biochar with a longer residence time. Due to the presence of vacuum, more volatilization occurs. An extension of the residence time causes further volatilization, but reduces the amount of biochar. A pyrolysis time of 30 minutes generated 67.6% magnetic biochar, which was significantly less compared to 85.9% at 10 minutes *(Thines et al. 2017).*

1.5 Hydropyrolysis: This is a fairly recent method, used to transform biomass into high-quality products by introducing hydrogen or hydrogen-derived substances into the reactor at a high pressure, usually higher than that of the atmosphere, between 50 bar and 200 bar *(Stummann et al, 2021).* The presence of hydrogen allows hydrogenation and polycondensation reactions. This processing is carried out

faster at high temperatures. Pyrolysis takes place at temperatures between 250 and 550 °C. It is essential to maintain a controlled flow of hydrogen gas *(Zheng et al, 2017; Stummann et al, 2020)*. High temperatures reduce both the concentration and volume of biochar obtained. The total amount of ash does not vary according to temperature, but is based on the base materials used *(Rombolà et al, 2016)*. The oxygen content of biochar can be decreased by using a catalyst during hydropyrolysis, which facilitates hydrocracking and thus improves the volume of biochar. A shorter residence time and high hydrogen pressure are recommended to enhance the amount of biochar. A hydrogen pressure of 1 MPa resulted in 26.1% of biochar, compared to higher hydrogen pressures *(Zheng et al, 2017; Chen et al, 2020)*.

1.6 Flash Pyrolysis: Flash pyrolysis is a thermochemical process that converts low-quality materials into high-quality biochar. This method is carried out with very fast heating speeds, thousands of degrees per second. Only certain types of reactors can withstand such high heating speeds, the most used being a special reactor. When raw materials are exposed to these high heating rates and an intense heat source, they move quickly and hit the inner walls of the reactor.

This leads to pyrolysis, a process by which materials are transformed into high-quality biochar. Rapid pyrolysis occurs at temperatures exceeding 400 °C. An increase in temperature can reduce the amount of biochar obtained, but it increases the amount of volatile substances. At 900 °C, biochar production was found to be 14,89 % by weight for palm kernel shell and 18,31 % for chlorella vulgaris microalgae, both of which were less than those obtained at 600 °C.

Since rapid pyrolysis takes place at high temperatures and with high heating rates, the surface of the carbon becomes smoother and the biochar particles become rounder. This process also leads to the formation of large aromatic structures in the resulting biochar *(Eibner et al, 2017; Maliutina et al, 2017)*.

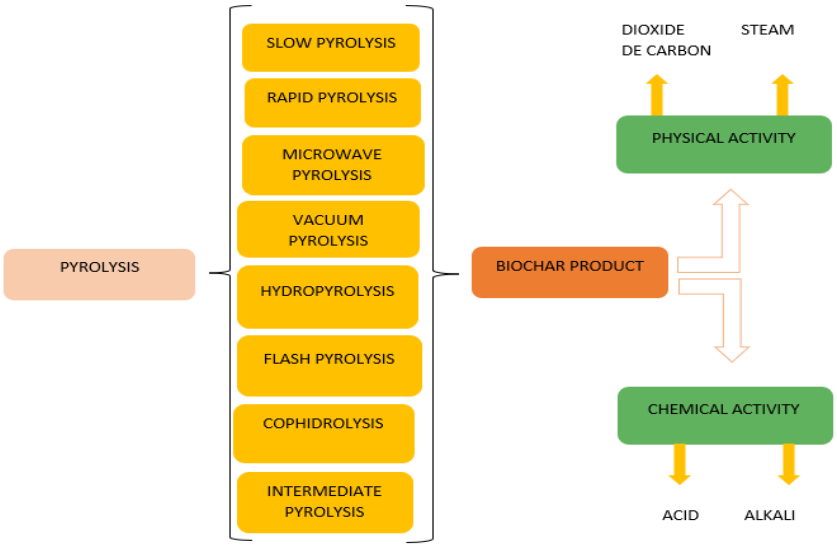

Fig. 2 - Types of pyrolysis to obtain biochar
(adapted from Dilipkumar 2021)

1.7 Co-pyrolysis: Co-pyrolysis is an efficient technique that combines two types of raw materials. This technique helps reduce heavy metal pollution by decreasing the amount of heavy metals in the material used. As a result, biochar obtains a hierarchical porous structure thanks to an environmentally friendly carbon additive. This helps to improve the physical and chemical characteristics of the biochar created. One of the main reasons for this is the efficient balancing of the elements in the raw material used by this method *(Zhao et al, 2017, 2018)*.

To achieve co-pyrolysis, a plug furnace is used. The two raw materials are mixed in appropriate proportions, depending on the type of materials used. During the process, the temperature is increased to a higher level, between 300-700 °C. It has been observed that the maximum yield for biochar from manure is 61%.

High temperatures help increase the strength of biochar *(Meng et al, 2018a)*. It is important that there are limited oxygen conditions during the process. After the material has been heated for a certain time, it cools rapidly to maintain the purity of the biochar. The 0:1 ratio had a yield of 54.87% for biochar, which was found to be maximum compared to other proportions of biomass feedstocks *(Huang et al, 2017; Meng et al, 2018b)*.

The amount of biochar produced depends on three aspects: temperature, ash content and the proportion of raw materials. The temperature and amount of ash are directly related to the yield of biochar. Co-pyrolysis positively influences pH, with biochar having higher pH values than the feedstock *(Meng et al, 2018a).* At high temperatures, the decomposition of raw materials is significant, and the aromatic degree of biochar improves *(Wang et al, 2018; Zhao et al, 2018).*

1.8. Intermediate pyrolysis: Intermediate pyrolysis depends on three process conditions, namely pyrolysis temperature, vapor residence time, and raw material residence time. Generally, intermediate pyrolysis is carried out under moderate temperature conditions, and the temperature between 450 and 550 °C is suitable for the complete conversion of raw materials into biochar. The overall performance for intermediate pyrolysis is higher than other conventional pyrolysis methods. A pyrolysis reactor is used to perform intermediate pyrolysis *(Ahmed et al, 2018; Luz et al, 2018).*

The pore size of the produced biochar is affected by the cell structure of the biomass, the maximum pyrolysis temperature, and the residence time. The BET surface area of biochar has been found to increase with increasing pyrolysis temperatures. The BET surface area (determined using the Brunauer-Emmett-Teller (BET) method indicating its porosity and adsorption capacity) of 128.706 was observed at 550 °C, which was greater than 121.377 at 450 °C *(Luz et al, 2018).* An increase in temperature increases the aromaticity of the biochar produced and the productivity rate of the biochar. Energy efficiency is inversely proportional to temperature *(Ahmed et al, 2018; Luz et al, 2018).*

2. Gasification

It is a chemical thermal process by which carbon-rich materials are broken down into gaseous products, including CO, CO2, CH4, H2 and trace amounts of hydrocarbons; these gases are known as syngas *(Dasappa et al, 2022).*

Gasification takes place at high temperatures, in the range of 700 to 900°C, in an environment with restricted oxidizing agents, such as oxygen, air, nitrogen, steam, carbon dioxide or a combination of these gases. It has been observed that as the temperature rises, the production of carbon monoxide and hydrogen increases, while other substances, such as methane, carbon dioxide and hydrocarbons, decrease. The main result of this process is syngas (mostly hydrogen), while coal is considered a by-product (or waste) with a lower efficiency, along with ash, tar and part of the oil. The partial oxidation of biomass, contrary to the combustion process, captures the energy available in biomass and brings it together in chemical bonds in the form of gaseous products. The inherent chemical energy of carbon in biomass is converted into combustible gases, which are more efficient and easier to use than raw biomass *(Matilo et al, 2022).*

Also, the commercial use of the gasification technique has been recorded. Due to its low emissions and higher volume of syngas, gasification outperforms traditional methods, including pyrolysis, combustion, and fermentation. The O/C ratio is crucial to achieve increased efficiency in gasification. High efficiency is achieved by using biomass with a low O/C ratio in the gasification process. The O/C ratio of biomass can be lowered by the roasting method. Before standard gasification, roasting can be seen as a preparatory step for achieving a higher quality of the product. It is a process carried out at low temperatures, between 200 and 300°C, with a heating rate of about 50°C/min, varying depending on the composition and type of biomass *(Sarker et al, 2021).*

Pyrolysis and gasification are interconnected processes. When these two methods are combined, there is no clear delineation between them.

The low proportion of oxygen used in the gasification process causes a partial oxidation of the biomass, affecting the characteristics of the final product. The type of product is among the most significant differences between pyrolysis and gasification. Gasification generates about 85% gaseous products, 10% solid coal and 5% liquid products. The diagram of the gasification process is illustrated in Figure (*Tripathi et al, 2016; Bisht et al, 2020*).

3. Torrefaction

It is a thermal processing process that improves the characteristics of biomass. The main process of torification from a chemical perspective consists of removing oxygen to create a solid product used as a combustible material or as a soil amendment. Torified biomass exhibits a lower O/C ratio compared to the original biomass *(Barskov et al, 2019).*

As a rule, torification is carried out by directly or indirectly heating the biomass to a temperature between 200 and 300 °C, applying a slow heating rate, up to 50 °C/min, for a duration of 20–120 minutes *(Wang et al, 2017).*

There are several types of torification, depending on the environment, which can be wet or dry, and depending on the method of production, which can be classified into four distinct techniques: oxidative, non-oxidative, acid tartar or steam explosion (fig.3) *(Chen, 2015).*

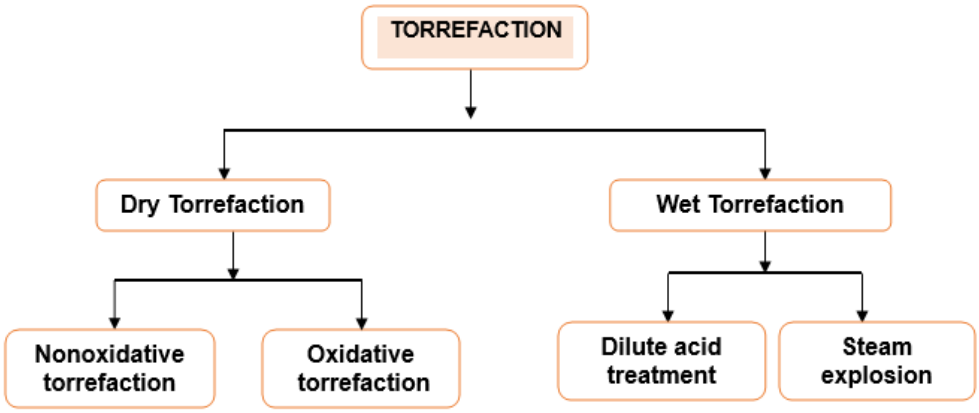

Fig. 3 - Types of torrefaction

The most common methods used for processing solid biomass are non-oxidative or conventional spinning. Realizing that non-oxidative torification is carried out under conditions similar to pyrolysis, except for lower temperatures, thermal processing is often referred to as light pyrolysis as well.

Regardless of the method or raw material used to obtain biochar, the moisture requirements and size are different for each method, but the process of obtaining biochar includes the following steps: First, the biomass raw material must be dried (the humidity should not exceed 15%).

Then, depending on the field of application, the material is shredded to the desired dimensions (the optimum is 8–12 mm). A belt conveyor is used to introduce the resulting biomass into a reactor, where it undergoes the heat treatment process.

This process removes moisture and volatile substances from biomass and produces biochar and other by-products such as syngas, tar, wood vinegar, and biogas. The usual process of obtaining biochar is illustrated in Figure 4.

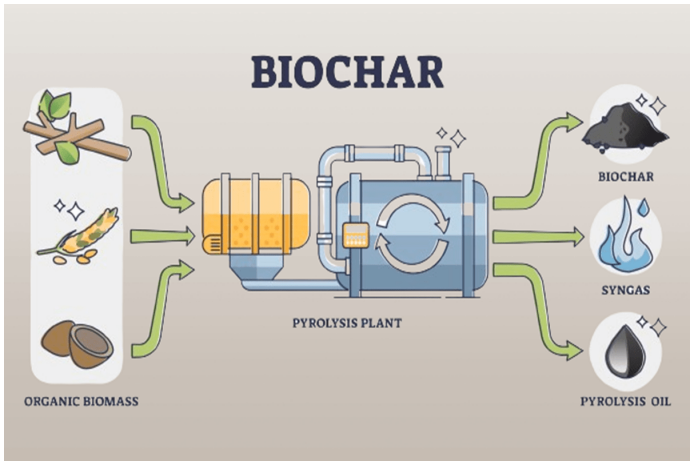

Fig. 4 - The standard process of obtaining biochar
(https://energytheory.com/wp-content/uploads/2023/12/biochar.png)

CONCLUSIONS

Biochar is a crucial component of the coming industrial revolution, helping to create a sustainable future and generating greater economic prosperity, increasing employment opportunities and improving the quality of life for people.

Due to its characteristics, biochar can be applied in multiple sectors, including agriculture, the food industry, construction, as well as in the pharmaceutical and cosmetic fields.

Depending on the type of raw material used for its production and the sector of application, it is necessary to carry out studies to determine the manufacturing method and the selection of the appropriate equipment.

Since the applications of biochar are closely related to its characteristics, future research needs to clarify the impact of the manufacturing process on biochar attributes. Biochar used for water purification will have distinctions from that intended for the energy sector or agriculture. In addition, there are numerous studies in the literature that analyze the influences of biochar on agriculture, especially in terms of agricultural production, influenced by different types of soil. For example, adding biochar can lead to an increase or decrease in crop yields, depending on soil types and fertilization management.

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EVALUATION OF NETTLE PARTS FOR FUNCTIONAL FOODS, BASED ON A NOVEL ANTIOXIDANT-DIETARY ELEMENT INDEX (ADEI)

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EVALUAREA PĂRȚILOR DE URZICĂ PENTRU ALIMENTE FUNCȚIONALE, PE BAZA UNUI INDICE NOU DE ANTIOXIDANȚI ȘI ELEMENTE NUTRITIVE

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ABSTRACT

Stinging nettle (Urtica dioica L.) is a widespread and sturdy plant with ancient value as a food and medicinal crop. The tight antioxidant and dietary profile of the plant suggests high potential as a food functional ingredient. For all that, limited comparative data are known on the nutritional value of nettle organs. In this contribution, the Antioxidant–Dietary Element Index (ADEI) is introduced as a simple method of ranking plant material by nutritional-related quality. Plant samples were collected from three sources to capture natural variation. Antioxidant activity was measured with the CUPRAC assay, polyphenol content with the Folin–Ciocalteu method, and the minerals iron (Fe) and zinc (Zn) with X-ray fluorescence (XRF).All results were combined in the ADEI index to provide a single comparative score for leaves, stems, and roots. The analysis demonstrated marked variations among plant organs. Leaves consistently exhibited the highest values, indicating superior antioxidant potential and enhanced mineral levels, whereas stems and roots showed comparatively lower functional properties. ADEI presents a simple but integrative way to highlight the nutritional value of plant material. Applied to nettle, it confirms the leaves as the most appropriate organ for functional food production and demonstrates the use of ADEI to valorize other medicinal and edible plants.

REZUMAT

Urzica (Urtica dioica L.) este o plantă răspândită și rezistentă, cu o valoare tradițională importantă atât ca aliment, cât și ca plantă medicinală. Profilul său bogat în antioxidanți și nutrienți sugerează un potențial ridicat ca ingredient funcțional pentru alimente. Cu toate acestea, există puține date comparative referitoare la valoarea nutrițională a diferitelor organe ale plantei. În această lucrare este introdus Indicele elementelor nutriționale-antioxidante (IENA din engl. ADEI) ca metodă simplă de ierarhizare a materialului vegetal în funcție de calitatea nutrițională. Probele de plante au fost colectate din trei surse pentru a surprinde variația naturală. Activitatea antioxidantă a fost măsurată prin metoda CUPRAC, conținutul de polifenoli prin metoda Folin–Ciocalteu, iar mineralele fier (Fe) și zinc (Zn) prin fluorescență de raze X (XRF). Toate rezultatele au fost combinate în indicele ADEI pentru a oferi un scor comparativ unic pentru frunze, tulpini și rădăcini. Analiza a evidențiat variații semnificative între organele plantei. Frunzele au prezentat în mod constant cele mai ridicate valori, indicând un potențial antioxidant superior și niveluri mai mari de minerale, în timp ce tulpinile și rădăcinile au arătat proprietăți funcționale mai reduse. ADEI oferă o metodă simplă, dar integratoare, de evidențiere a valorii nutriționale a materialului vegetal. Aplicat la urzică, acesta confirmă frunzele ca fiind cele mai potrivite pentru producerea de alimente funcționale și demonstrează utilitatea indicelui ADEI pentru valorizarea altor plante medicinale și comestibile.

INTRODUCTION

Stinging nettle (*Urtica dioica* L.) is a widespread wild plant that has long been valued both as food and as a natural remedy. In recent years, it has gained growing attention for its high content of bioactive compounds and essential minerals, which contribute to its many health benefits *(Bhusal, 2022)* Nettle has traditionally been appreciated in both nutrition and phytotherapy for its rich content of polyphenols, vitamins,

and antioxidants, as well as essential minerals including iron, calcium, magnesium, and zinc. Together, these elements account for their well-documented health-promoting effects *(Maietti et al., 2021).*

In recent years, the growing interest in functional foods has emphasized the need for systematic approaches that evaluate plant-based resources not only for their antioxidant capacity but also for their nutritional mineral composition. Although many studies have investigated the phytochemical profile of nettle roots, stems, and leaves, comprehensive comparisons that consider both antioxidant activity and mineral nutritional content remain relatively scarce *(Adhikari et al., 2015).* To advance knowledge in this area, we apply the Antioxidant–Dietary Element Index (ADEI) as a novel integrative approach. This tool unites antioxidant properties and mineral content into a single evaluative criterion, offering a more complete assessment of nettle organs. Such an approach helps highlight the most useful components for functional food design and opens new avenues for food and nutrition research.

Iron stands out as one of the most critical essential minerals. It is fundamental to the formation of hemoglobin and myoglobin, thereby supporting oxygen transport and energy production, while also playing a key role in maintaining immune defense and cognitive performance *(NIH, 2022; Hurrell, 2010).* Iron deficiency continues to be the most widespread nutritional disorder worldwide, leading to anemia, reduced vitality, and hindered development, with the greatest impact seen in vulnerable groups (*WHO, 2001).*

While iron derived from plant foods is absorbed less efficiently than heme iron, nettle still makes a noteworthy dietary contribution and stands out as a potential resource for reducing micronutrient deficiencies *(Adhikari et al., 2015; Bhusal, 2022)*. Iron is an essential trace element for plants, playing key roles in photosynthesis, respiration, and in the synthesis of cofactors required for electron transport and numerous enzymatic processes *(Connorton et al., 2017)*. Since iron is often poorly available in soils and can become harmful when present in excess, plants have evolved sophisticated mechanisms for their uptake, translocation, storage, and regulation in order to maintain internal balance *(Connorton et al., 2017).*

Zinc represents another vital trace element and is the second most prevalent metal in the human body after iron. It acts as a cofactor for over 300 enzymes and is indispensable for immune function, growth and development, neurological activity, and reproductive processes *(Prasad, 2013; NIH, 2021).* Zinc deficiency is considered a major global health problem, linked to reduced immune function, slower growth, and a higher risk of infections (*Wessells & Brown, 2012).* The zinc present in nettle enhances its value as a functional food, complementing antioxidant effects with important nutritional benefits *(Maietti et al., 2021).*

The aim of this study is to present and apply a new Antioxidant–Dietary Element Index (ADEI) as a comprehensive tool for evaluating nettle parts, according to their nutritional and functional significance. By integrating antioxidant capacity with essential mineral content into a single indicator, the ADEI offers a clearer understanding of how various plant parts contribute to human health. This method not only highlights the nettle fractions with the greatest potential for functional food development but also enhances our knowledge of the relationship between dietary minerals and antioxidant activity in shaping the plant's overall health value.

Integrating antioxidant activity with essential dietary minerals in the ADEI highlights the nutritional value and functional potential of nettle.

MATERIALS AND METHODS

Collection and preparation of nettle plants

Soil and nettle samples were collected during the autumn of 2023 and 2024 from three locations in Romania: L1 - Timișoara (Timiș County), L2 - Vadu-Dobrii (Hunedoara County) and L3-Turcinești (Gorj County). At each location, materials were carefully separated into four categories: soil, roots, stems and leaves, and thoroughly rinsed with distilled water. The samples were then air-dried at room temperature to constant weight, ground into a fine homogeneous powder, and subsequently prepared for analysis.

Samples analysis

The moisture content [%] of the soils and nettle samples were determined by thermogravimetric analysis using a Sartorius balance, as described by Bordean et al, 2013. The determination of total polyphenolic content (TPC) was performed using Folin–Ciocalteu colorimetric method, which remains one of the most widely employed assays for polyphenol quantification in plant-derived materials *(Bordean, 2016).* Total antioxidant capacity (TAC) was determinate using CUPRAC method which measures how the antioxidants in the samples reduce copper ions and form a coloured complex. The intensity of this colour reflects the strength of the antioxidant activity, making the method simple, reliable, and suitable for evaluating a wide range of natural compounds *(Apak et al., 2004).* For the XRF (X-ray fluorescence)

analysis, powdered samples were examined using a Hitachi X-MET8000 portable spectrometer *(Tarkanyi et al., 2023*). XRF spectrometry is highly valuable as it allows the rapid and precise determination of both the concentration and presence of chemical elements in a sample *(Yonehara et al., 2010).* All determinations and measurements were performed in triplicate and reported to fresh weight (FW).

Definition and calculation of Antioxidant-Dietary Element Index (ADEI)

ADEI is not a standardized indicator but more a composite indicator concept proposed by the authors for functional food assessment based on the indicators described by Wang et al., 2022 and Vahid et al., 2020.

The ADEI (equation 1) combines bioactive compounds (equation 2) and essential dietary minerals (equation 3) into a single score, enabling direct comparison across samples. This approach makes it possible to rank plant organs or locations by their nutritional and functional potential, to identify the most suitable candidates for functional food development, and to present results in a clear and integrative manner *(Vahid et al, 2020)*.

ADEI was calculated as:

ADEI = Antioxidant score × Micronutrient factor

ADEI > 1 → High functional potential (antioxidants + essential minerals combined)

ADEI ≈ 0 → Very low nutritional/functional relevance (either very low TPC/TAC or Fe/Zn)

Ranking helps sorting ADEI descending, highlighting which samples are most promising for functional food applications.

Where:

$$\mathbf{ADEI} = \frac{TPC_{norm} + TAC_{norm}}{2} \times \left(1 + \frac{Fe_{norm} + Zn_{norm}}{2}\right) \quad (1)$$

$$Antioxidant\ Score = \frac{TPC_{norm} + TAC_{norm}}{2} \quad (2)$$

$$Micronutrient\ Factor = 1 + \frac{Fe_{norm} + Zn_{norm}}{2} \quad (3)$$

- TPC_{norm} = Total Polyphenol Content normalized to 0–1 by dividing by the maximum value in the dataset.

- TAC_{norm} = Total Antioxidant Capacity normalized.

- Fe_{norm}, Zn_{norm} = Iron and Zinc concentrations normalized.

Normalization of each variable is described by equation 4.

$$X_{norm} = \frac{X}{X\ max} \quad (4)$$

Where X_{max} *is the highest value in the dataset for that variable.*

RESULTS

The calculated results for ADEI are presented in table 1.

Table 1

Antioxidant, micronutrient and ADEI values of nettle samples

Sample	TAC_{norm}	TPC_{norm}	Fe_{norm}	Zn_{norm}	Antioxidant Score	Micronutrient Factor	ADEI
NL3	1	1	0.052	0.361	1	1.207	1.207
NL2	0.75	0.8	0.039	0.892	0.775	1.465	1.135
							Table 1 continued
NL1	0.697	0.485	0.028	0.227	0.591	1.128	0.666
NS3	0.352	0.337	0.038	0.689	0.345	1.363	0.47
NS2	0.111	0.337	0.067	1	0.224	1.533	0.344
NR2	0.118	0.194	0.075	0.463	0.156	1.269	0.198
NS1	0.148	0.174	0	0.186	0.161	1.093	0.176
NR1	0.135	0.168	0.01	0.06	0.151	1.035	0.157
NR3	0.066	0.194	0.062	0.332	0.13	1.197	0.155
SO1			0.396	0.363		1.379	
SO2			1	0.569		1.785	
SO3			0.266	0.122		1.194	

Legend: NR = nettle roots; NL = nettle leaves, NS= nettle stems; 1,2,3 =collection areas; TPC= total polyphenols contents; TAC = total antioxidant capacity normalization; Fe_{norm}= iron concentrations normalized, Zn_{norm}=zinc concentrations normalized; ADEI= Antioxidant-Dietary Element Index

Based on the calculated ADEI values, the leaf samples (NL3, NL2, NL1) obviously rank highest, confirming that nettle leaves combine both strong antioxidant potential (TPC and TAC) and appropriate levels of Fe and Zn. Among them, NL3 reached the top score, indicating the most promising balance between polyphenol content, antioxidant activity, and micronutrient density. Stem and root samples (NS3, NS2, NR2, NR3) show intermediate ADEI values, suggesting they still contribute functional compounds but at lower effectiveness compared to leaves. For soil TAC and TPC were not analyzed (ND).

Our results demonstrate that integrating polyphenol content (TPC), antioxidant capacity (TAC), and essential minerals (Fe, Zn) into a single composite score (ADEI) provides a powerful way to rank nettle samples by their nutritional and functional potential (Figure 1).

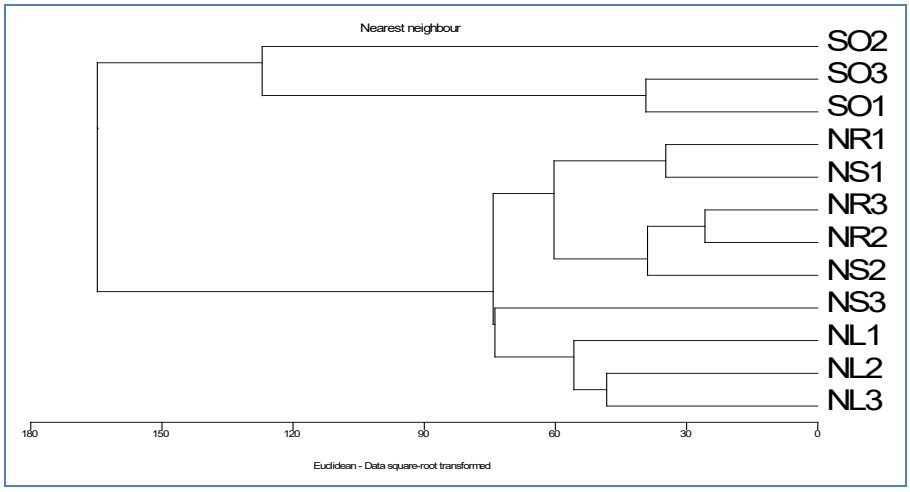

Fig. 1 - Dendrogram as a result of cluster analyses

Legend: NR = nettle roots; NL = nettle leaves, NS= nettle stems; 1,2,3 =collection areas;

This figure presents a graphical representation of clusters obtained by using cluster analyses based on squared root transposed data and Euclidian nearest neighbor equation. The dendrogram groups soil data in cluster 1(SO2, SO3, SO1) and cluster 2 where the plant parts corresponding to roots and stem appear mixt while the vectors corresponding to leaves data NL1, NL2, NL3 are grouped together.

The same cluster analyses offer a second dendrogram figure 2 which groups the antioxidant characteristics together TPC and TAC parameters well connected to Fe and Zn and the indicator ADEI showing a direct link to water content.

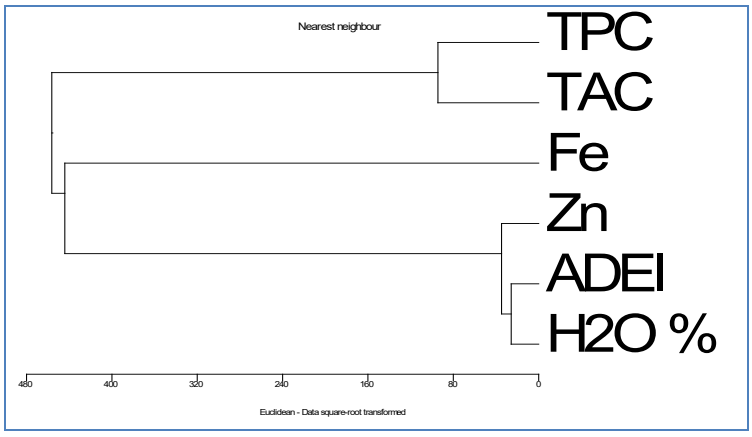

Fig. 2 - Dendrogram of antioxidant and minerals based on cluster analyses

Legend: H2O% = moisture content of samples; TPC= total polyphenols contents;
TAC = total antioxidant capacity normalization; Fe= iron concentrations, Zn=zinc concentrations;
ADEI= Antioxidant-Dietary Element Index

As we can observe from both figures, the leaves exhibited the highest ADEI values, highlighting them as the most promising plant parts for incorporation into functional food formulations. As a comprehensive and user-friendly indicator, ADEI facilitates the evidence-based selection of plant organs and

collection locations, offering meaningful guidance for product formulators and nutrition specialists in determining the most appropriate raw materials.

Iron content generally increases from the root to the leaf, although at location 3 higher amounts were found in both roots and leaves. In the case of zinc, the greatest concentration occurred in the stem at location 2, while at location 3 the stem contained more zinc than the leaf, and the root had the lowest levels.

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Figure 3 and Table 1 show that iron strongly influences mineral composition and bioactive compounds (TAC and TPC). In Timiș (location 1), lower iron levels correspond to moderate TAC and TPC values. Whereas in Hunedoara (location 2), the highest iron concentrations are associated with increased antioxidant capacity and polyphenol content, suggesting a direct correlation. In location 3 (Gorj), although iron levels are lower than in Hunedoara, TAC and TPC record the highest values, confirming that, in addition to iron, other local factors contribute to the antioxidant potential. These results therefore highlight a complex relationship between iron and bioactive compounds, specific to each collection area.

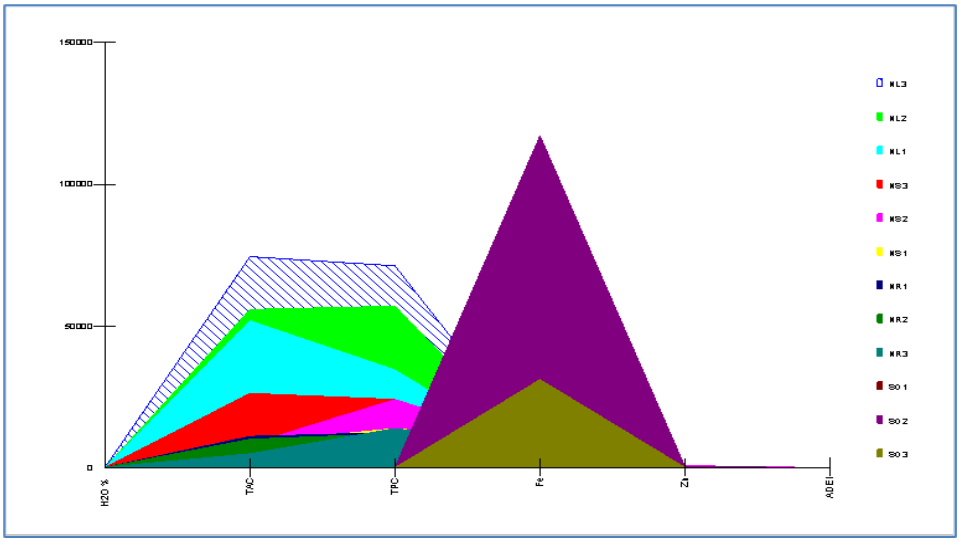

Fig. 3 - Fingerprint-influence of essential minerals and antioxidants on TAC and TPC

Legend: H2O= moisture content of plant samples (%); TPC= total polyphenols contents; TAC = total antioxidant capacity; NR = nettle roots; NL = nettle leaves, NS= nettle stems; 1,2,3 =collection areas;

The fingerprint of nettle illustrated in figure 3 highlights the variations in mineral and bioactive compounds across plant organs and collection areas. The biochemical fingerprint defines the plant's identity, reflecting the diversity of compounds expressed in different organs and growing regions. More than a simple compositional profile, it allows samples to be distinguished, ensures traceability and authentication of raw materials, and highlights their nutritional and therapeutic importance. In this way, biochemical fingerprint functions both as a research tool and as a practical standard for quality assessment and applied purposes.

CONCLUSIONS

Stinging nettle (*Urtica dioica* L.) exhibits notable nutritional and functional potential, and the Antioxidant–Dietary Element Index (ADEI) offered an integrative view of the differences among roots, stems, and leaves. Of these organs, leaves consistently proved to be the most valuable, combining greater antioxidant capacity with higher levels of essential minerals, thus representing the most suitable fraction for functional food applications.

The evaluation across the three collection sites highlighted the influence of soil composition and mineral availability, especially iron, on the levels of bioactive compounds. At the same time, variations observed between locations indicate that additional environmental factors also shape the biochemical profile of nettle, giving each site a distinctive "fingerprint."

By combining different parameters into a single index, ADEI has proven to be an effective and straightforward tool, bringing together antioxidant activity and mineral content in one comprehensive score.

This method makes data easier to interpret while also supporting evidence-based choices in the use and valorization of plant resources.
Nettle shows once again that it is a valuable plant, with its leaves being the main part used for developing functional foods. In addition, the ADEI approach can also be applied to other edible and medicinal plants, giving researchers, nutritionists, and product developers a useful tool to explore and make full use of natural resources.

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The results of the scientific study will be included in the PhD Thesis of Patricia Cristina Tarkanyi.

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CFD-BASED INVESTIGATION OF A COUNTER-ROTATING VERTICAL AXIS WIND TURBINE FOR LOW-WIND AGRICULTURAL ENVIRONMENTS

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INVESTIGAȚIE NUMERICĂ BAZATĂ PE CFD A UNEI CONFIGURAȚII CONTRAROTATIVE DE TURBINE EOLIENE CU AX VERTICAL PENTRU MEDII AGRICOLE CU VÂNT REDUS

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Keywords: *Lenz, numerical simulation, vorticity magnitude, tip speed ratio*

ABSTRACT

This paper reports a computational fluid dynamics (CFD) analysis of a counter-rotating Lenz-type vertical axis wind turbine (VAWT) that can be used in low-wind agricultural settings. The main aim was to quantitatively assess the aerodynamic performance and flow behaviour of the suggested configuration. An unsteady Reynolds-averaged Navier–Stokes (URANS) model considering shear stress transport (SST) turbulence was used in conjunction with ANSYS Fluent to solve the unsteady rotor–stator interaction. The turbine configuration consisted of two counter-rotating three-bladed rotors with a diameter of 0.3 m, a rotor height of 0.6 m, and a blade chord length of 0.12 m. Simulations were performed for a uniform inlet wind speed of 12 m/s at a tip speed ratio of 0.2 to 1.2. Results indicate the counter-rotating configuration achieved power output readings between 50 W and 120 W with their corresponding variability in torque coefficient, which reflected the best operating conditions for the tested TSR range. Flow field visualisation demonstrated extreme vorticity magnitude in the rotors' region, indicating intense wake interaction that impacted entire turbine performance. The outcome of these tests illuminates the potentiality of counter-rotating Lenz-type VAWTs as a feasible small-scale power alternative for decentralised energy supply in low-wind agricultural settings. Future activities will consider three-dimensional simulations to simulate spanwise flow effects and contrast the two-dimensional results with experimental results from wind tunnel testing. Parametric optimisation of spacing between rotors, blade shape, and rotational speed ratio between the two rotors for maximum efficiency over a range of wind conditions will also be considered.

REZUMAT

Această lucrare prezintă o analiză computațională de dinamica fluidelor (CFD) a unei configuratii contra-rotative de turbine eoliene cu ax vertical (VAWT) de tip Lenz, care poate fi utilizată în medii agricole cu vânt slab. Scopul principal a fost evaluarea cantitativă a performanței aerodinamice și a comportamentului de curgere al configurației sugerate. Un model Navier-Stokes nestaționar, cu mediere Reynolds (URANS) si model de turbulenta SST, a fost utilizat împreună cu ANSYS Fluent pentru a rezolva interacțiunea rotor-stator. Configurația consta insuprapunerea a două rotoare cu trei pale, care se rotesc în sens inverssi care au un diametru de 0,3 m, o înălțime a rotorului de 0,6 m și o lungime a corzii palelor de 0,12 m. Simulările au fost efectuate pentru o viteză uniformă a vântului la intrare de 12 m/s, la un raport al vitezei la vârf de 0,2 până la 1,2. Rezultatele indică faptul că configurația a atins valori de putere de ieșire între 50 W și 120 W, cu variabilitatea corespunzătoare a coeficientului de cuplu, ceea ce a reflectat cele mai bune condiții de funcționare pentru gama TSR testată. Vizualizarea câmpului de curgere a demonstrat o magnitudine extremă a vorticității în regiunea rotoarelor, indicând o interacțiune intensă care a influentat întreaga performanță a turbinei. Rezultatul acestor teste evidențiază potențialul turbinelor de tip VAWT contrarotative de tip Lenz ca o alternativă energetică fezabilă la scară mică pentru alimentarea descentralizată cu energie în medii agricole cu vânt redus. Activitățile viitoare vor lua în considerare simulări tridimensionale pentru a simula efectele de curgere pe lungime și vor compara rezultatele bidimensionale cu rezultatele experimentale din testele în tunelul aerodinamic. De asemenea, se va lua în considerare optimizarea

parametrică a distanței dintre rotoare, a formei palelor și a raportului vitezei de rotație dintre cele două rotoare pentru o eficiență maximă într-o gamă largă de condiții de vânt.

INTRODUCTION

Wind turbines are a key technology for harnessing wind energy, and quantifying their efficiency is crucial to enhance performance and reduce costs. As the demand for renewable energy increases, wind energy is emerging as a dominant force in the world energy mix (*Gielen D.et al., 2019)*.

The classical theory offers a simplification analytical approach to determine the efficiency of wind turbines basically based on Betz's Law and momentum theory (*Sørensen, J. N, 2016)*. It makes simplifying assumptions and fails to accurately depict complex aerodynamic phenomena such as turbulence and eddy interactions.

Figure 1 shows wind speed (in m/s) with wind power density (in W/m²) on a graph with a logarithmic scale. It shows how quickly power density increases with increasing wind speed since power in winds is related cubically to speed. Principal indicators, such as the mean annual value, maximum hourly and ten-minute means, and maximum hundred-year, are depicted to represent the extremely large variations in wind speed and theoretical energy.

The graph illustrates how minimal increases in wind speed significantly raise available wind energy.

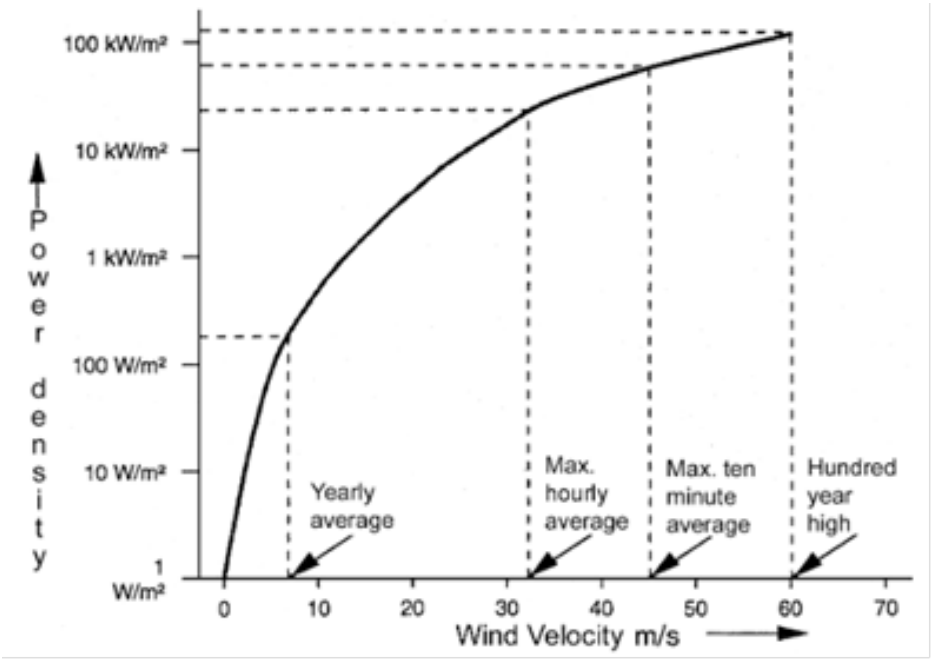

Fig. 1 - Power curve of a wind turbine showing the relationship between wind speed and power output
(Wagner, H. J., 2020)

In Figure 2 are illustrated the lift and drag forces on wind turbine blade and how the airfoil shape and direction of the wind produce torque for power production. The wind strikes the blade at an angle of attack to the chord line (a straight line connecting the leading and trailing edges).

This encounter generates two main aerodynamic forces: lift perpendicular to the wind direction (this is the main force responsible for spinning the blade) and drag in the same direction as the wind and opposing the movement of the blade.

The wind drag force manifests itself as a horizontal force component and one that assists in energy extraction. Even though the point of pressure is the point upon which the resultant aerodynamic force acts, gravity and the plane along which the turbine revolves are incorporated to place the forces the turbine feels when rotating into perspective.

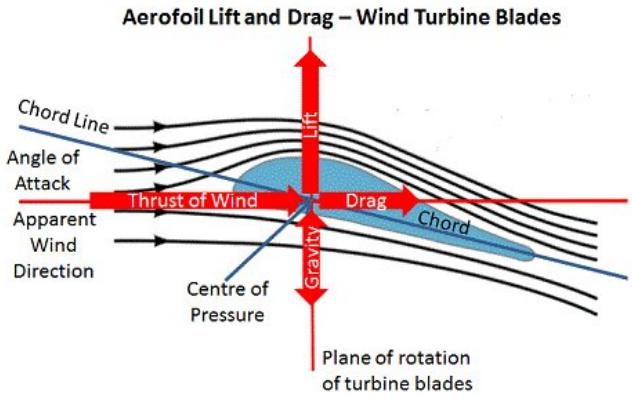

Fig. 2 - Aerodynamic lift and drag force on the blade
(*Chintan Kariya, 2017)*

Computational Fluid Dynamics (CFD) is a numerical method to simulate fluid flow and evaluate in detail the aerodynamic performance of wind turbines. CFD is different from BEM and classical theory because it accounts for intricate effects such as vortex effects, turbulence, and flow separation (*Bianchini, A. et al., 2017)*. The Navier-Stokes equations are the governing equations for the simulation of CFD, which describe the motion of fluids:

$$\rho\left(\frac{\partial v}{\partial t} + v \cdot \nabla v\right) = -\nabla p + \mu \nabla^2 v + f \tag{1}$$

where: v is the fluid velocity field, ρ is the fluid density, p is the pressure, μ is the dynamic viscosity, and f represents body forces, such as gravity.

CFD simulations allow for detailed, high-resolution modelling of the interactions between wind turbine blades and the wind, providing insights into blade shape optimization, turbine spacing, and the effects of vortex interaction (*Calautit, K. et al., 2018)*, (*Chowdhury, A. M. et al., 2016)*, (*Delafin, P. L., 2017)*.

The image below shows a computational fluid dynamics (CFD) simulation showing the magnitude of vorticity around a wind turbine rotor. The colour scale on the left indicates the magnitude of vorticity (in s^{-1}), from blue (low) to red (high). The circular boundary represents the area swept by the rotor, with the turbine hub at the center. Regions of high vorticity (yellow, red) appear near the blade tips and behind them, indicating strong vortex shedding - typical of rotating blades.

The downstream structure behind the rotor exhibits complex flow interactions that are crucial for understanding trailing losses, turbine efficiency, and turbine spacing in wind farms. These flow patterns are important in evaluating aerodynamic performance and in load predictions.

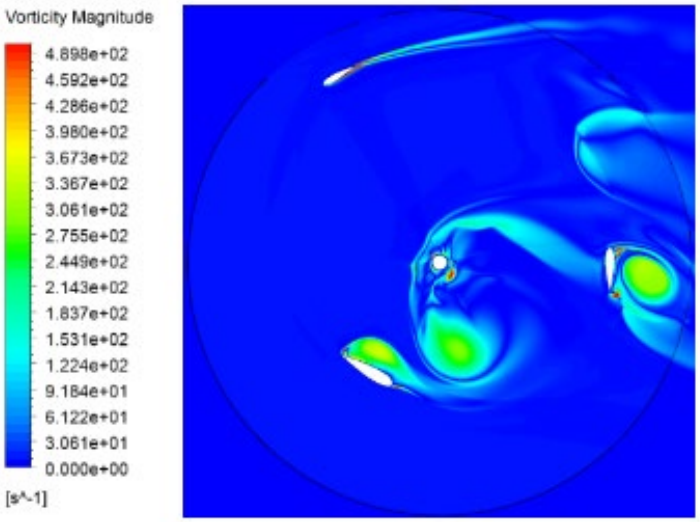

Fig. 3 - CFD simulation showing wind flow over turbine blades
(*Malael, I. et al., 2021)*

Recent advances in wind turbine performance evaluation have led to the development of hybrid models, which combine the advantages of BEM theory and CFD simulations. These hybrid models allow for rapid performance estimates (from BEM) while providing accurate aerodynamic analysis (from CFD). In addition, Artificial Intelligence (AI) (*Al Noman, A. et al., 2022)* and Machine Learning (ML) (*Cheng, B. et al., 2022)* are used to analyze large data sets, predict turbine performance, and optimize operational parameters.

Fig. 4 illustrates the structure and shape evolution of a wind turbine, both in instantaneous and time-averaged perspectives. The top view shows the tip and hub vortices generated by the rotating blades. These vortices create complex and dynamic flow patterns.

This turbulent, unsteady flow has significant implications for the downstream turbines (e.g., fluctuating loads and power). While the bottom view shows the flow divided into three regions: the induction region: just upstream of the rotor, where the wind slows down due to the turbine resistance; the near region: directly behind the rotor, showing a velocity deficit Δu^- and coherent vortex structures; the far region: further downstream, where the wake expands and partially recovers its velocity u^-.

The velocity deficit is most significant near the turbine and gradually decreases downstream.

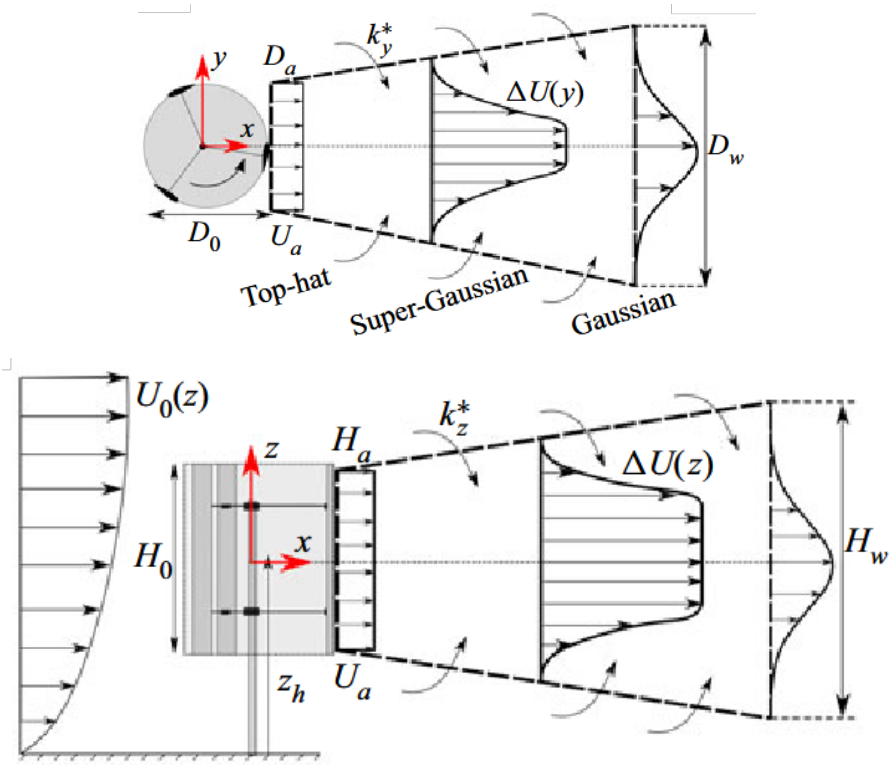

Fig. 4 - Schematic figure showing the flow regions resulting from the interaction of a wind turbine and the turbulent inlet boundary layer

(*Ouro, P.et al., 2021)*

CFD allows the prediction of aerodynamic forces on wind turbine blades, including lift and drag (*Qi, Y, et al., 2025),* (*Huish, C. et al., 2025)*. The main challenge in wind turbine CFD is to capture the effects of turbulence, the transient nature of the wind, and the interaction of the rotating turbine blades with the wind.

Fig. 5 illustrates the computational grid used to simulate the flow over the airfoil of a wind turbine blade, showing several zoom levels from the domain scale to the blade surface. The global grid view (a) shows the overall computational domain, with a fine grid resolution concentrated around the airfoil (center) and coarser cells in the opposite direction.

This is a typical grid structure, designed to save computational resources. The in-focus region (b) is a zoomed-in view of the refined area surrounding the airfoil. A tighter grid grouping can be observed, especially where accurate flow prediction (e.g., vortex generation) is crucial.

The airfoil neighbourhood (c) shows unstructured grid elements around the airfoil, capturing the complex boundary layer behavior and flow separation zones, while the airfoil surface grid (d) is a further zoom in close to the airfoil surface with dense triangular grid elements, essential for resolving the boundary layer flow. Finally, the LE and TE insets show close-ups of the leading edge (LE) and trailing edge (TE),

which feature an extremely fine grid—essential for accurate modelling of pressure gradients and flow separation.

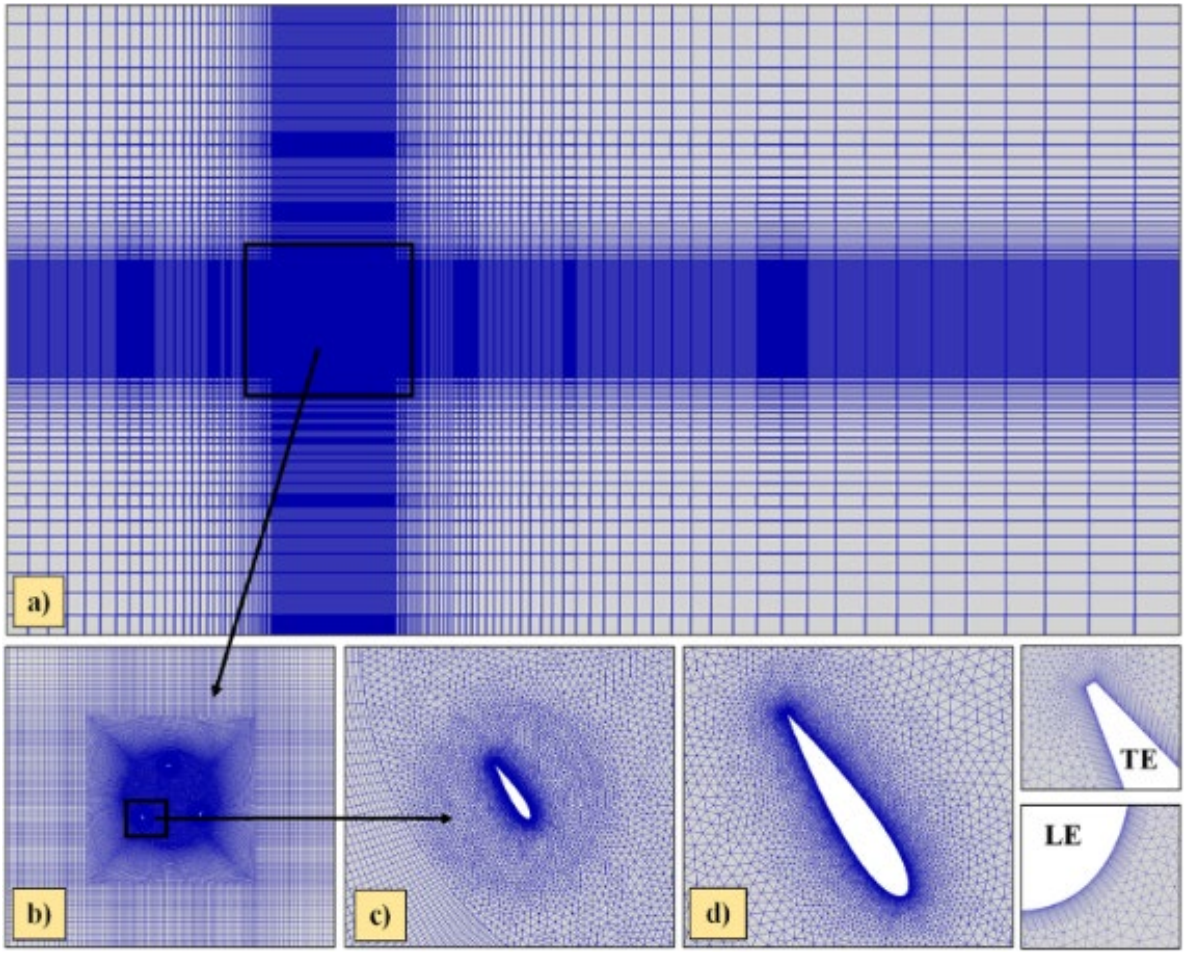

Fig. 5 - Hybrid computational grid for a vertical axis wind turbine of type H: a) structured stationary domain; b) blocks around the rotational domain; c) fine unstructured grids inside the rotational domain; d) grid density on the blade surfaces, leading edge (LE) and trailing edge (TE)
(*Fatahian, E. et al., 2024)*

For wind turbine simulations, accurate turbulence models are essential to predict velocity profiles and power losses (*Cabezon, D. et al., 2011)*. Some commonly used models include:

- model k-ε (Reynolds-Averaged Navier-Stokes (RANS)),
- model k-ω,
- Large Eddy Simulations (LES), which resolves large turbulence scales.

Turbulence models, such as the k-ε, are often used in simulations to approximate the effects of turbulence on flow:

$$\frac{\partial k}{\partial t} + u \cdot \nabla k = \nabla \cdot (v_t \nabla \mathrm{k}) + P_k - \varepsilon \quad (2)$$

where: k is the turbulent kinetic energy (m2/s2), ε – the dissipation rate (m2/s3) and Pk – the turbulent production term.

The predictions of the turbulent wake behind a body (or a section of a wind turbine blade) for different computational models are shown in Fig. 6. This figure highlights the superiority of LES over RANS in capturing the unsteady and turbulent wake dynamics, aligning more closely with experimental data.

This is important for accurate prediction of behavior in wind turbine panels and aerodynamic applications.

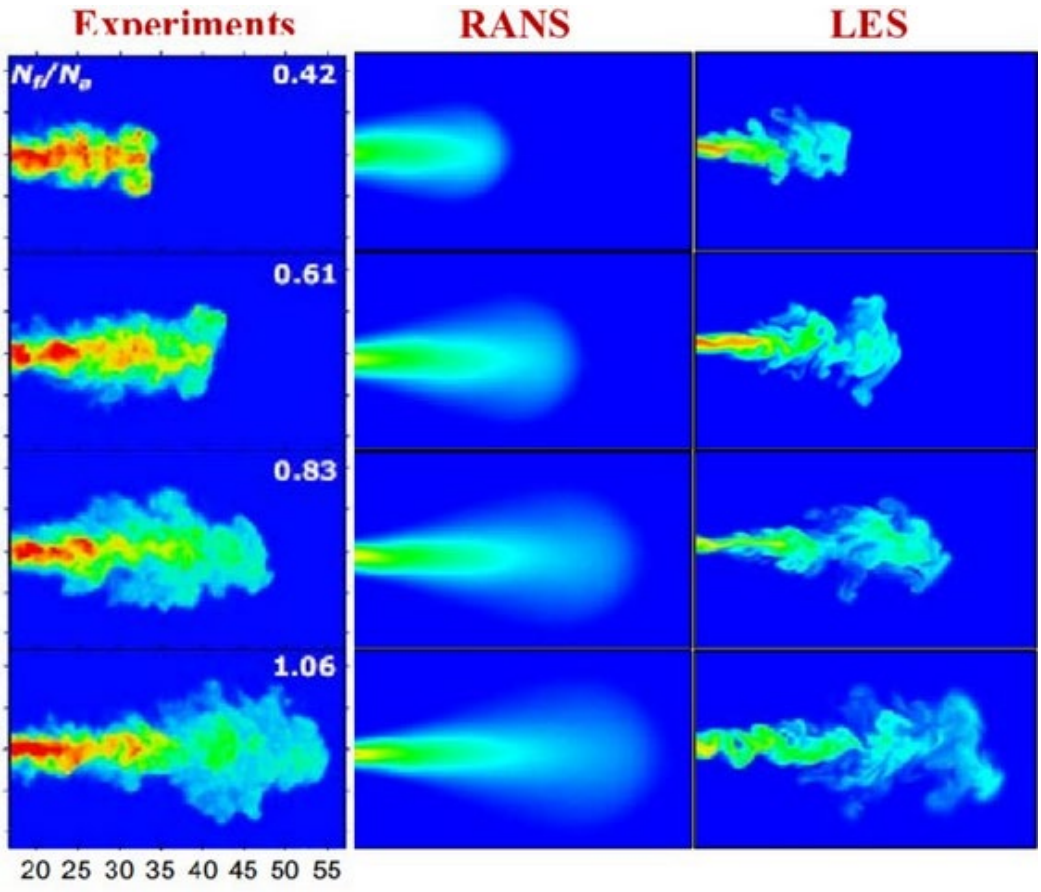

Fig. 6 - Images comparing the equivalence ratio calculated using RANS and LES models
(Som, S. et al., 2012)

In this article, the efficiency of a new vertical axis wind turbine configuration consisting of two counter-rotating Lenz-type wind turbines which will be tested in a wind tunnel was numerically analyzed. The analysis was performed using CFD methods.

MATERIALS AND METHODS

For the development of the counter-rotating vertical axis turbine, its operating parameters were established. This wind turbine is vertical axis and is of the Lenz type (*Gall, M. et al., 2022)*, based on the drag force.

The system of vertical axis wind turbines with dual counter-rotating rotor (Fig. 7), consisting of an upper rotor (1) formed by a set of Lentz-2 type blades (2), which rotates in one direction and a lower rotor (13) with a second set of Lentz-2 type blades (*Bucur, I. O. et al., 2021)* (11), mounted coaxially and rotating in the opposite direction, having coaxial counter-rotating axes (4) which allow the independent rotation of the two sets of blades, characterized in that the coaxial counter-rotating axes (4) are connected to a double-rotation electric generator (6) whose stator and rotor rotate in opposite directions to obtain a double relative speed, thus optimizing the mechanical conversion into electricity and which is provided with a conductive slip ring with inductive coupling (8) which makes possible the contactless transfer of electrical energy from the generator to the electrical box on the support being fixed to the turbine support pole (12) by means of a support flange (7) comprising vibration damping mechanisms (3) and (10) on which UFC type oscillating bearings are mounted, fixed to the turbine support column (12) by means of support flanges (5) and (9), to reduce mechanical stresses.

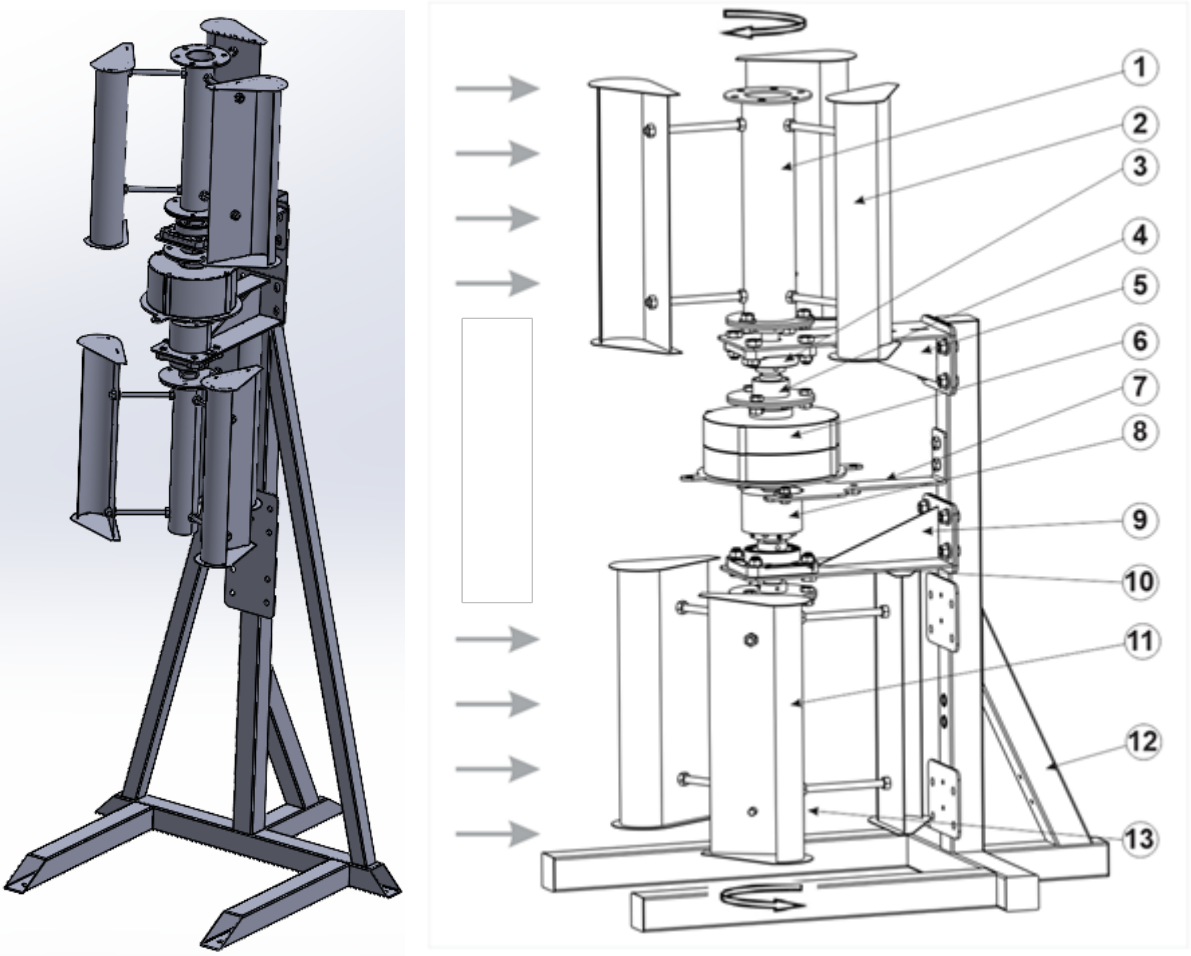

Fig. 7 - CAD model for Lenz type counter-rotating wind turbine

The power coefficient (performance) Cp is determined from the wind power at the turbine shaft. The equations below represent the formula for estimating the power of a wind turbine.

$$P_{wind} = \frac{1}{2}\rho \cdot S \cdot V_{\infty}^{3} \cdot C_p \tag{3}$$

where: P_{wind} is the wind power, ρ 1.225 kg/m3 is the air density, S (m2) is the reference surface, V_{∞} is the wind speed and Cp is the power coefficient.

$$C_{pT} = \frac{P_T}{P_{wind}} = \frac{M \cdot \omega}{\frac{1}{2}\rho S V_{\infty}^{3}} = \frac{\frac{1}{2}\rho S V_{\infty}^{2} L C_m \omega}{\frac{1}{2}\rho S V_{\infty}^{3}} = C_m \frac{L \cdot \omega}{V_{\infty}} = C_m \cdot \lambda < 0.593 \tag{4}$$

To determine the turbine blade chord length, the relative solidity of the turbine rotor radius was expressed, resulting in the parameters in Table 1.

Table 1

Operating parameters for vertical axis wind turbine

V[m/s]	D[m]	c[m]	N	TSR	omega[rad/s]	delta t(2 deg)	it (8 spins)	N [rpm]
12	0.3	0.12	3	0.2	16	0.002182	1440	152.788746
				0.4	32	0.001091		305.577491
				0.6	48	0.000727		458.366237
				0.8	64	0.000545		611.154982
	H[m]			1	80	0.000436		763.943728
	0.6			1.2	96	0.000364		916.732473

The computational domain and grid are created in Ansys Meshing 2024 R1. Using CFD (Computational Fluid Dynamics) simulations, the moment coefficient that will be used to determine the power coefficient can be determined. The equations are solved using the commercial code Fluent. The computational grid for this study is shown in Fig. 8.

The images show the mesh used for the CFD (computational fluid dynamics) simulations of the vertical axis wind turbine (VAWT) model. This mesh was used to discretize the flow domain so that the Navier-Stokes equations governing fluid flow can be solved numerically. The refinement near the turbine ensures an accurate capture of flow separation, vortices, and other aerodynamic effects around the blades.

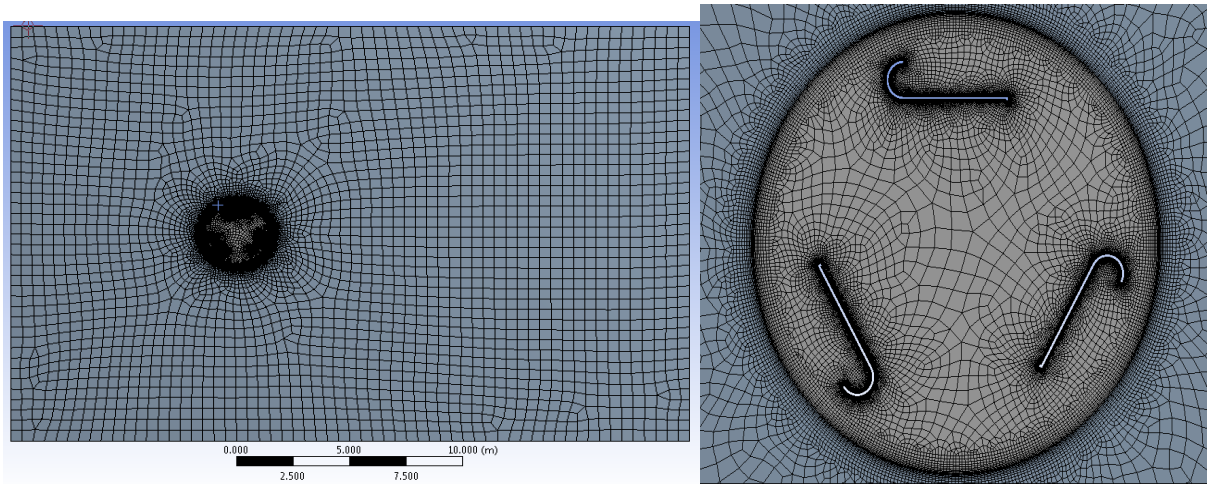

Fig. 8 - The grid made with Ansys Meshing

The first complete turbulence model was introduced by Kolmogorov in 1941 - k-ω, where ω is the specific rate of dissipation of turbulent kinetic energy. The form in which it is defined eliminates the wall functions used to calculate the parameters governing the flow in the vicinity of the walls. This model involves the use of a more efficient calculation grid in the boundary layer area.

The model is extremely sensitive to the variation of the initial conditions, so small variations of ω in the inlet section drastically influence the final results. F.R. Menter built the k-ω SST (Shear Stress Transport) model in 1999.

This is a combination of the standard k-ε model and the k-ω model, using k-ε for the free flow area considered totally turbulent and the k-ω model for the boundary layer.

The transition from one model to the other is ensured by using some fitting functions that activate the k-ε or k-ω formulation depending on the area and by introducing a diffusive term in the transport equation of ω.

For the analysis, the Reynolds number was calculated to be 1e06 and the Menter's Shear Stress Transport (SST) turbulence model was used to perform transient simulations. This model consists of 2 transport equations, which are part of the classical k-omega formulation.

The transport equation for turbulent kinetic energy k:

$$\frac{\partial k}{\partial t}+\bar{u}\frac{\partial k}{\partial x}+\bar{v}\frac{\partial k}{\partial y}+\bar{w}\frac{\partial k}{\partial z}=\frac{1}{\rho}\left[\frac{\partial}{\partial x}\left(\Gamma_k\frac{\partial k}{\partial x}\right)+\frac{\partial}{\partial y}\left(\Gamma_k\frac{\partial k}{\partial y}\right)+\frac{\partial}{\partial z}\left(\Gamma_k\frac{\partial k}{\partial z}\right)\right]+\widetilde{G_k}-Y_k \quad (5)$$

Transport equation for specific dissipation ω:

$$\frac{\partial \omega}{\partial t}+\bar{u}\frac{\partial \omega}{\partial x}+\bar{v}\frac{\partial \omega}{\partial y}+\bar{w}\frac{\partial \omega}{\partial z}=\frac{1}{\rho}\left[\frac{\partial}{\partial x}\left(\Gamma_{\omega}\frac{\partial \omega}{\partial x}\right)+\frac{\partial}{\partial y}\left(\Gamma_{\omega}\frac{\partial \omega}{\partial y}\right)+\frac{\partial}{\partial z}\left(\Gamma_{\omega}\frac{\partial}{\partial z}\right)\right]+G_{\omega}-Y_{\omega}+D_{\omega} \quad (6)$$

where: Γ_k and $\Gamma_\omega$represent the effective diffusivity of k and ω; D_ω^+- the positive portion of the cross-diffusion term; $\widetilde{G_k}$- turbulent kinetic energy production; G_ω – generation of ω.

A first step in setting up the case in the CFD software Ansys Fluent is represented by importing the calculation grid, checking the quality and setting the type of analysis (steady or unsteady). The settings of the case in Ansys Fluent are presented below in Table 2.

Table 2

Case settings in the ANSYS-Fluent 2024 R1 solver

Models	Solver	Pressure Based	Unsteady	3d
	Viscous Model	k-ω SST		
Materials	Air	Density, constat		
Operating conditions	Pressure 101325 [Pa]			
Boundary Condition	Intrare	Velocity inlet: V_x=12m/s		
	Pale	wall		
	Ax	wall		
	Interfata	Interface rotor-stator		
	Rotor	Mesh motion		
	Stator	Stationary		
Solve	Controls	Solution	Courant nr=2	Discretization 2nd order upwind
	Initialize	Intrare		
	Monitors	Residuals	10^{-6}	
		Force	Momentum coeficient	
	Iterate	10^6 Steps	0.001s time step size	
Report	Reference values	Intrare	Length=raza turbinii	

The residuals for all variables decrease rapidly in the first few hundred iterations, indicating that the solution converges well initially (Fig. 9). After about 200 iterations, the residuals level off and oscillate around small values (between 1e-04 and 1e-06 for most variables). The plot indicates that the solution “converges” at iteration 1840, with residuals in the order of 1e-04 to 1e-07, which is generally acceptable for CFD simulations. Oscillations and stagnation at small residual values are common in unsteady simulations or when dealing with complex flow physics such as turbulence.

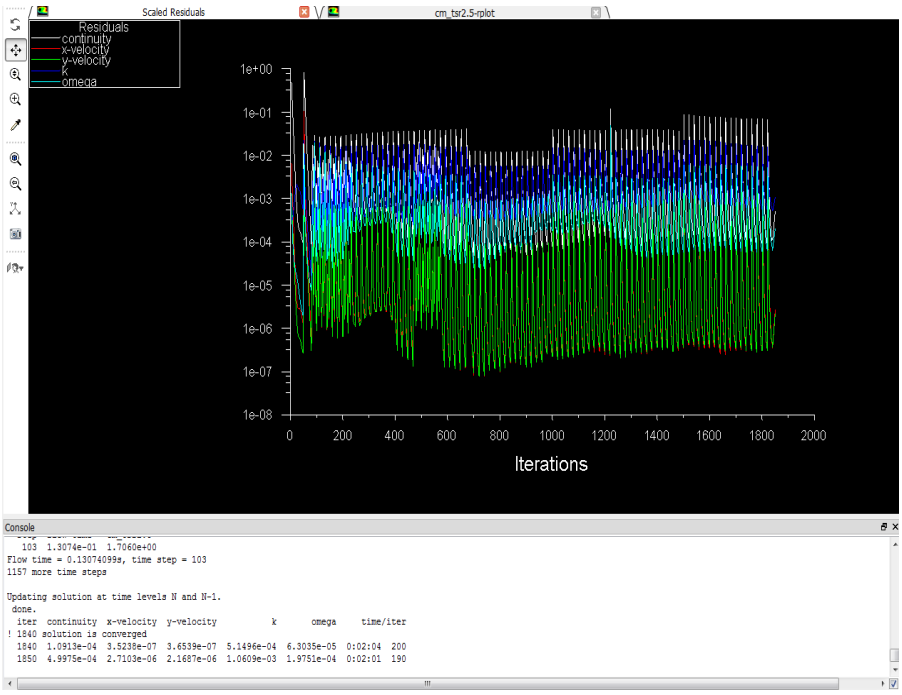

Fig. 9 - Evolution of residues

RESULTS

In the post-processing stage of the numerical data obtained from the unsteady analyses, the recirculation zones and their influence on the wind turbine performance were analyzed. The variation of the moment coefficient for different values of the TSR was also monitored. Following this step, the turbine operating characteristic was obtained, which consists of the graphic representation of the variation of the power coefficient as a function of the TSR (tip speed ratio).

The graph below represents the variation of the torque coefficient Ct as a function of the azimuth angle θ for different tip speed ratios (TSR) of the vertical axis wind turbine. On the X axis is represented the azimuth angle (theta) in degrees, varying from 0° to 360°, representing a complete rotation of the turbine blade, and on the Y axis is represented the torque coefficient (Ct), which measures the momentum generated in relation to the available wind energy. Each curve corresponds to a different TSR value, ranging from 0.2 to 1.2.

At lower TSRs (0.2; 0.4), the power factor exhibits more pronounced peaks and troughs. As the TSR increases, the peaks become less sharp and the curve smooths out. The highest Ct values appear to be close to TSRs of 0.2 and 0.4, indicating a good performance even at these low TSRs.

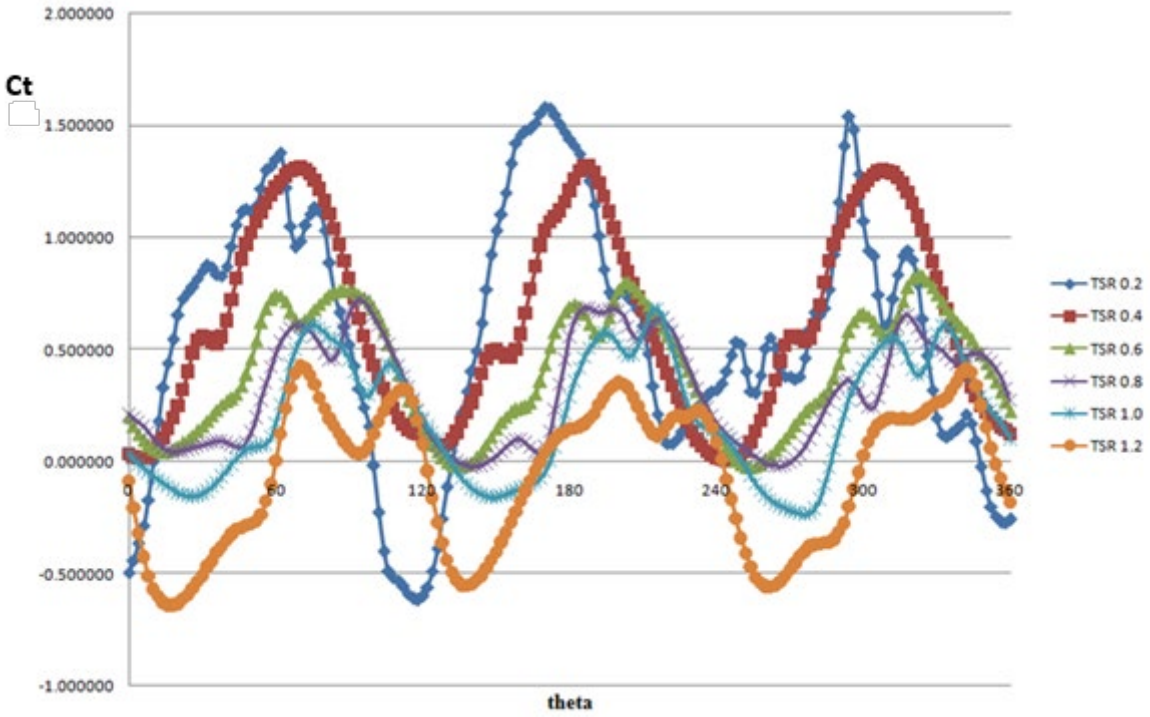

Fig. 10 - Variation of the torque coefficient

Fig. 11 and Fig. 12 show CFD (Computational Fluid Dynamics) visualizations of the vorticity magnitude around the vertical axis wind turbine, captured at different blade positions. The vorticity magnitude is represented by the colour scale at the bottom, ranging from low (blue) to high (red) values. Vortex indicates local rotation of fluid particles, related to turbulence and vortex structures.

Each panel (a, b, c, d) shows the flow field and vortex formation around the turbine blades at different angles. The turbine rotor area is delimited by a circle, showing the blade positions and the flow wake inside.

The regions near the blade tips and leading/trailing edges show high vorticity (yellow to red), indicating strong vortex shedding. Vortices form and break up downstream, creating a complex wake of interacting vortex structures. The differences between the panels show how the vorticity evolves as the blades rotate, highlighting unstable aerodynamic phenomena.

Vortex break-up influences the aerodynamic forces on the blades, affecting power output and structural loads. Understanding the distribution of vorticity helps optimize blade design and spacing to reduce losses and fatigue.

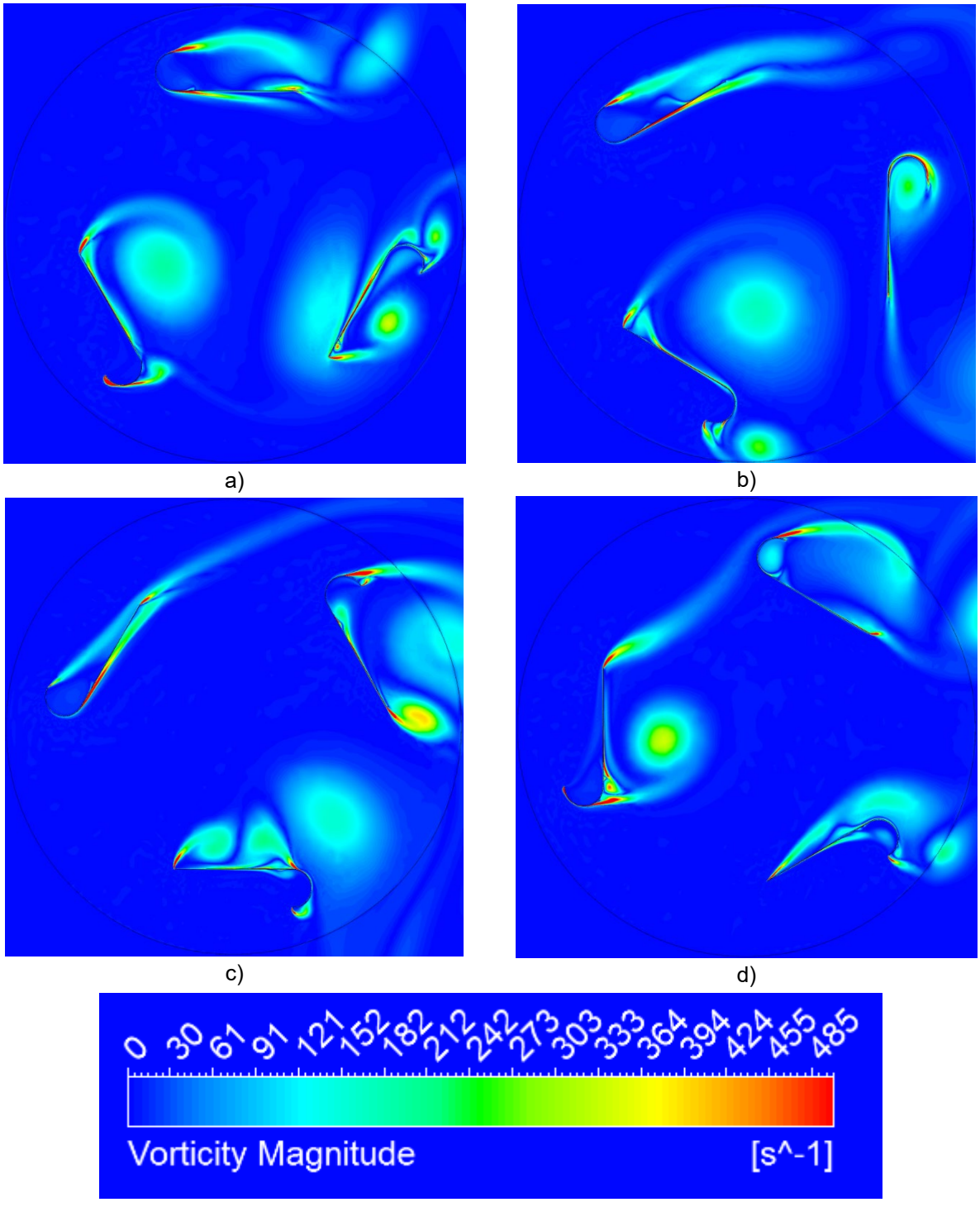

Fig. 11 - Variation of vorticity magnitude for TSR 0.4
a) 0 degree; b) 30 degrees; c) 60 degrees; d) 90 degrees.

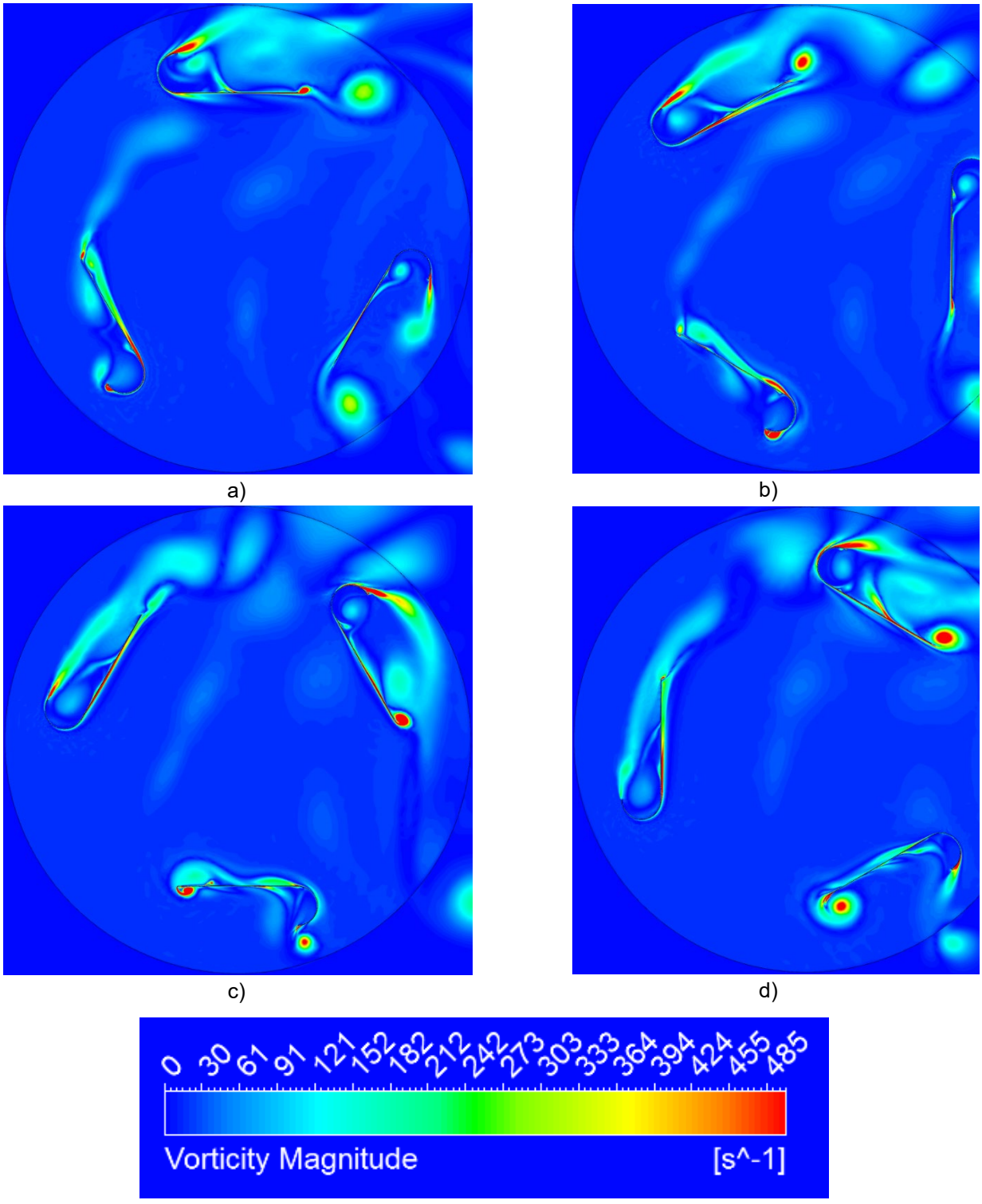

Fig. 12 - Variation of vorticity magnitude for TSR 0.8
a) 0 degree; b) 30 degrees; c) 60 degrees; d) 90 degrees.

CONCLUSIONS

This research presented a numerical investigation of a novel vertical axis wind turbine (VAWT) design featuring two Lenz-type turbines rotating in opposite directions. The study objective was the aerodynamic performance and flow features of this new configuration by means of three-dimensional (3D) Computational Fluid Dynamics (CFD) simulations with ANSYS Fluent 2024 R1.

Simulations were conducted at a steady wind speed of 12 m/s and a range of changing tip speed ratios (TSR) from 0.2 up to 1.2. The SST (Shear Stress Transport) turbulence model was employed in order to capture the unsteady and separated flow around the rotating blades.

Torque fluctuation throughout a full revolution was analyzed for each TSR. The results show that under low TSRs (i.e., 0.2–0.4), the turbine experienced high torque fluctuations due to dominant unsteady flow effects and periodic flow separation. As the TSR increased, the torque behavior became stabilized, with the optimal performance at 0.8, which represented an optimal operating range for the configuration. The counter-rotation arrangement appeared to reduce torque asymmetry and phase lag between the two turbines, resulting in a smoother mechanical output.

The vorticity magnitude contours provided insightful information on the dynamics of the interaction flow between the two counter-rotating rotors. At mid-to-high TSRs, vortex interaction between the rotors created more evenly distributed wake structures and interference zones that were reduced in size. This imply that there are aerodynamic benefits of the opus configuration, particularly in terms of wake loss reduction and improvement in downstream flow quality.

Despite the positive results, there were certain limitations to the study. The simulations were restricted to 10 full revolutions owing to computational cost, and this can limit the long-term evolution of the flow and statistical convergence of unsteady phenomena. In addition, only one wind speed was analyzed, and the rotor geometry was not optimized.

To overcome these restrictions, a physical model of the turbine has been designed and will be wind tunnel tested. Future work will include experimental verification of CFD predictions, as well as further parametric studies including blade profile optimization, rotor spacing, and dynamic stall modeling. More simulations at varied inflow conditions and yaw angles are also on the horizon to check the design's robustness under realistic operating scenarios.

In conclusion, the proposed turbine concept design has positive aerodynamic characteristics, including stable torque generation and constructive vortex interactions under design operating conditions. The findings confirm the feasibility of the configuration as an efficient and compact wind energy product for distributed power systems, particularly for variable direction and moderate wind speed conditions.

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CHICKPEA PRODUCTIVITY UNDER BIOTIC AND ABIOTIC STRESSES: CURRENT STATUS AND PERSPECTIVES

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PRODUCTIVITATEA NĂUTULUI ÎN CONDIȚII DE STRES BIOTIC ȘI ABIOTIC: SITUAȚIA ACTUALĂ ȘI PERSPECTIVE

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Keywords: *chickpea, biotic stress, abiotic stress*

ABSTRACT

Chickpea (Cicer arietinum L.) is the second most important legume crop globally, playing a vital role in food security and sustainable agriculture. Its productivity is significantly affected by biotic stresses such as diseases and pests, as well as abiotic stresses including drought, salinity, and extreme temperatures. This article reviews the physiological, biochemical, and molecular mechanisms underlying chickpea responses to these adverse conditions, alongside current breeding strategies and agronomic practices aimed at improving resilience. Integrated understanding of these factors is essential for developing high-performing varieties capable of stable yields under changing climatic conditions.

REZUMAT

Năutul (Cicer arietinum L.) este a doua cea mai importantă leguminoasă cultivată la nivel global, cu un rol esențial în securitatea alimentară și agricultura durabilă. Productivitatea sa este însă afectată semnificativ de stresuri biotice, precum boli și dăunători, și abiotice, cum ar fi seceta, salinitatea și temperaturile extreme. Acest articol sintetizează principalele mecanisme fiziologice, biochimice și moleculare prin care năutul răspunde acestor condiții adverse, precum și strategiile actuale de ameliorare genetică și practici agronomice pentru creșterea rezilienței. Înțelegerea integrată a acestor aspecte este esențială pentru dezvoltarea unor soiuri performante, capabile să asigure o producție stabilă în contextul schimbărilor climatice globale.

INTRODUCTION

Chickpea (*Cicer arietinum* L.) (Figure 1) holds the esteemed position of being the second most cultivated and consumed legume crop globally *(FAOSTAT. FAO)*. It is widely distributed in the tropics, subtropics, and temperate regions *(Anbessa, Y. et al, 2009)*, and is believed to have originated in present-day southeastern Turkey and the surrounding regions of Syria *(Van der Maesen, L.J.G., 1987; Negusse, H. et al, 2025)*. Chickpea is an annual herbaceous crop belonging to the genus *Cicer*, with cultivation extending to more than 50 countries worldwide, covering a total area of 12.14 million hectares and an annual production of 11.30 million tons *(Food and Agriculture Organization of the United Nations, 2012)*. Major producing countries include Canada, India, Myanmar, Pakistan, Turkey, Ethiopia, Iran, Mexico, Australia, and the USA *(Singh, V. et al, 2020)*, with northwestern Mexico representing one of the key regions of production. Ethiopia, for instance, ranks among the six largest chickpea-producing countries globally and is the leading producer, consumer, and exporter of chickpeas in Africa, accounting for more than 14% of its legume production, with 0.46 million tons produced on 0.22 million hectares *(Rawal, V.N.D.K. et al, 2019; Akpo, E. et al, 2021; CSA 2021; Sori, A. et al, 2025)*.

Chickpea plays a crucial role in global food security. Legume seeds are a staple in the diet of many people worldwide, particularly in poorer regions where access to animal protein such as meat, fish, and dairy is limited *(Martín-Cabrejas M. A., 2019; Castañeda, A.L. et al, 2025)*. Chickpeas are highly nutritious, with seeds containing 20–30% protein, 40% carbohydrates, and 3–6% oil *(Gil, J. et al, 1996)*. They also provide a rich source of bioactive compounds, including amino acids, fatty acids, polysaccharides, phenolic compounds, antioxidants, and other phytochemicals *(Johnson, N.A.N. et al, 2024; Kaur, R., Prasad, K.,*

2021; Khalid, W. et al, 2025). In addition to human nutrition, chickpea stover serves as a nutrient-rich supplement for livestock during lean seasons *(Li, H. et al, 2015)*. Beyond its nutritional value, chickpea is an important crop in sustainable farming systems, being often grown in rotation with cereals as a disease break and contributing to soil fertility through atmospheric nitrogen fixation *(Singh, K. B., 1997).*

Fig. 1 - Chickpea (*Cicer arietinum* L.) *(The Global Bean Project)*

Despite its global importance and adaptability, chickpea productivity is seriously constrained by multiple stresses. Growth, development, and yield are strongly influenced by climatic and environmental conditions *(Saeed, M., 2024)*.

This legume is particularly sensitive to heat stress during the reproductive stage, leading to reduced flowering, flower abortion, and poor pod formation, which collectively represent a major limiting factor for yield *(Naveed, M. et al, 2025)*.

Furthermore, chickpea productivity is hindered by both biotic and abiotic factors, including diseases, insect pests, drought, salinity, and heavy metal toxicity *(Shehzadi, K. et al, 2025)*. These stresses remain the major bottlenecks for achieving yield stability and expanding chickpea production worldwide.

MATERIALS AND METHODS

1. Major Abiotic Stresses in Chickpea Cultivation

Chickpea productivity is strongly influenced by climatic and pedological conditions of the cultivation environment, with abiotic stresses such as drought, salinity, and extreme temperatures representing the main yield-limiting factors. These conditions trigger complex physiological and biochemical responses that negatively affect germination, vegetative growth, pod formation, and seed filling.

1.1. Drought

Drought is the most frequent and severe abiotic stress affecting chickpea cultivation (Table 1), particularly in the semi-arid regions of South Asia, East Africa, and the Middle East. During the reproductive stages—especially flowering and seed-filling—water deficit leads to a reduction in the number of fertile flowers, increased flower abortion, and a drastic decrease in pod formation.

Table 1

Major abiotic stresses affecting chickpea and their effects

Stress Type	Region/Example	Effect on Plant	Tolerant Mechanisms	References
Drought	South Asia, East Africa, Middle East	Reduced flowering, flower abortion, poor pod formation	Deep roots, osmolyte accumulation (proline, soluble sugars), LEA proteins	*Negusse, H. et al, 2025; Kashiwagi, J. et al, 2006.*
Salinity	Global (20% agricultural land)	Reduced photosynthesis, chlorophyll, nutrient imbalance	Ion exclusion (Na^+/Cl^-), K^+/Na^+ homeostasis, antioxidant enzymes (SOD, CAT)	*Eyasu, W. et al, 2025*
Heat	India, Pakistan, Ethiopia	Pollen sterility, ovule inviability, reduced pod set	Heat shock proteins (HSPs), membrane stability, transpiration cooling	*Soren, K. R. et al, 2021*
Heavy Metals / UV	Mining areas, polluted soils	Reduced germination, impaired metabolism	Detoxifying enzymes, restricted uptake	–

According to studies by *Negusse, H. et al, 2025*, severe drought can reduce chickpea yield by up to 70%, depending on the genotype and the timing of stress occurrence. Tolerant genotypes are characterized by deep rooting, rapidly responsive stomata, and increased accumulation of osmolytes such as proline and soluble sugars. In addition, tolerance is often associated with the activation of genes involved in free radical detoxification, osmotic stress regulation, and the synthesis of LEA (Late Embryogenesis Abundant) proteins.

1.2. Salinity

Soil salinization affects over 20% of global agricultural land, and chickpea is moderately sensitive to this stress. The presence of toxic ions such as Na^+ and Cl^- interferes with the uptake of essential nutrients (K^+, Ca^{2+}), reducing the plant's ability to maintain osmotic balance and optimal photosynthetic function.

Several studies have shown that salinity decreases photosynthetic efficiency and chlorophyll content while increasing lipid peroxidation, indicating cellular membrane damage. Tolerant genotypes respond by accumulating proline, regulating ion transport (maintaining a favorable K^+/Na^+ ratio), and activating antioxidant enzymes such as SOD and CAT. A recent study by *Eyasu, W. et al, 2025,* demonstrated that the application of natural biostimulants can mitigate the effects of salinity by enhancing the antioxidant system and improving growth parameters.

1.3. High Temperatures

Heat waves associated with climate change increasingly affect chickpea growing regions, particularly in India, Pakistan, and Ethiopia. Temperatures above 35°C during the flowering period lead to pollen sterility, reduced ovule viability, and impaired synthesis of hormones involved in pod development.

Heat stress triggers the accumulation of reactive oxygen species (ROS) and causes denaturation of structural and enzymatic proteins. Thermotolerant genotypes maintain better cooling capacity through transpiration, exhibit high membrane stability, and have increased levels of heat shock proteins (HSPs). Additionally, QTL loci associated with high-temperature tolerance have been identified and can be utilized in molecular breeding programs.

1.4. Other Relevant Abiotic Stresses

Although less frequent, stresses caused by UV radiation, heavy metal pollution (e.g., Cd and Pb), or unsuitable soil pH can also affect chickpea development and productivity. In particular, in areas affected by mining activities or excessive irrigation, the accumulation of sodium or toxic metals reduces plant viability and interferes with fundamental metabolic processes.

2. Biotic Stresses: Major Diseases and Pests in Chickpea Cultivation

Although chickpea is relatively tolerant to unfavorable environmental conditions, its productivity is severely affected by a range of biotic stresses, particularly diseases caused by fungi, bacteria, and viruses, as well as attacks by specific insect pests (Figure 2). Under favorable conditions for the pathogens or pests, these factors can lead to yield losses of up to 100% in untreated cases or in the absence of resistant genotypes.

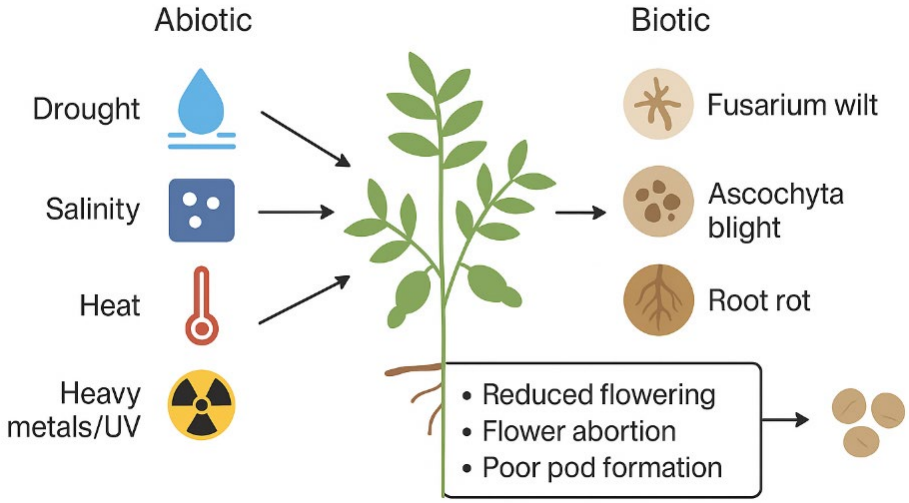

Fig. 2 - Major Abiotic and Biotic Stresses Affecting Chickpea Productivity

2.1. Vascular Wilt – Fusarium oxysporum f. sp. Ciceris

This is one of the most devastating diseases of chickpea, prevalent in hot and dry regions of South Asia, East Africa, and the Middle East. The pathogen invades the root system and colonizes the vascular tissues, leading to gradual wilting of the plant. Symptoms include chlorosis, browning of vascular tissues, and eventual collapse of the entire plant.

Physiological races vary by region, complicating the selection of resistant genotypes. Genetic tolerance is controlled by one or more major loci, and breeding efforts include the introgression of resistance genes from traditional genotypes or wild species *(Jimenez-Gasco, M. M. et al, 2004)*.

2.2. Ascochyta Blight – Ascochyta rabiei

Ascochyta blight is a destructive foliar disease, common in regions with relatively high humidity. The pathogen produces circular lesions on leaves, stems, and pods, accompanied by visible pycnidia. In advanced stages, the infection leads to complete necrosis of the aerial parts.

The plant's response to *Ascochyta rabiei* involves the rapid activation of genes related to phytoalexin synthesis, accumulation of phenolic compounds, and strengthening of cell walls. Disease management relies on a combination of resistant cultivars, crop rotation, and fungicide treatments *(Varshney, R. K. et al, 2019)*. *Fusarium* wilt and *Ascochyta* blight are the most devastating diseases (Table 2).

Table 2

Major biotic stresses affecting chickpea productivity

Stress Type	Causal Agent	Symptoms	Yield Loss	Control Strategies	References
Vascular wilt	Fusarium oxysporum f. sp. ciceris	Chlorosis, browning, wilting	Up to 80%	Resistant genotypes, crop rotation	*Jimenez-Gasco, M. M. et al, 2004*
Ascochyta blight	Ascochyta rabiei	Leaf, stem, pod lesions; necrosis	High	Resistant varieties, fungicides, rotation	*Varshney, R. K. et al, 2019*
Root rot	Rhizoctonia solani, Sclerotium rolfsii	Necrotic roots, stunted seedlings	Moderate to high	Biocontrol (Trichoderma spp.), resistant varieties	-
Insect pests	Helicoverpa armigera	Flower, pod, seed damage	Up to 90%	Selective insecticides, pheromone monitoring, transgenic lines	-
Storage	Sitophilus spp.,	Seed weight	Post-harvest	Drying <9% moisture,	-

pest	Callosobruchus chinensis	loss, reduced germination	losses	bioinsecticides, hermetic storage	

2.3. Root Rot – Rhizoctonia solani, Sclerotium rolfsii

This disease affects young plants, especially in warm and moist soils, causing necrosis of roots and basal stems. Early infections result in poor emergence or death of seedlings. Effective control involves the use of biocontrol agents (*Trichoderma* spp.), soil sterilization, and the cultivation of partially resistant varieties.

2.4. Viruses and Phytoplasmas

Although less frequent, viral infections such as Chickpea stunt disease (transmitted by leafhoppers – *Orosius albicinctus*) or Bean yellow mosaic virus can have a major impact on yield. These infections cause stunting, chlorosis, leaf deformation, and reduced pod formation. No effective treatments exist, making preventive measures essential, including off-season planting to avoid vector activity and the use of certified seeds.

2.5. Major Pests

Helicoverpa armigera (pod borer)

This species is considered the most important chickpea pest worldwide. The larvae feed on flowers, pods, and developing seeds. Damage can reach up to 90% in the absence of control measures. Management strategies include the use of selective insecticides, pheromone-based monitoring, and the development of transgenic lines (e.g., Bt-chickpea, still under research).

Sitophilus spp. and Callosobruchus chinensis (storage pests)

They affect seeds during storage. These beetles reduce seed weight, germination viability, and nutritional quality. Control measures include drying seeds to below 9% moisture, applying bioinsecticidal treatments, and using hermetic packaging.

3. Physiological and Biochemical Responses of Chickpea to Stress

Chickpea adaptation to biotic and abiotic stresses involves a range of integrated responses at the morphophysiological, biochemical, and molecular levels. These mechanisms enable the plant to survive and partially maintain productivity under stress conditions by conserving water, reducing oxidative losses, and regulating hormonal balance. This section presents the main adaptations documented in recent scientific literature.

3.1. Responses to Water Stress

Under drought conditions, chickpea activates a series of mechanisms to conserve water and maintain essential physiological functions (Figure 3):

- **Stomatal closure** – reduces transpiration but also limits photosynthesis;
- **Decrease in osmotic potential** – through accumulation of compatible osmolytes (proline, glycine betaine, soluble sugars);
- **Deeper roots** – tolerant genotypes (e.g., ICC 4958) exhibit an extensive root system, efficient in extracting water from deep soil profiles *(Kashiwagi, J. et al, 2006)*;
- **Reduction of leaf area** – minimizes water loss through transpiration.

3.2. Regulation of Oxidative Balance

Most stresses (drought, salinity, heat, pathogens) lead to the accumulation of reactive oxygen species (ROS) – unstable molecules that damage lipids, proteins, and DNA.

To counteract this, plants activate antioxidant systems, such as:

- **Superoxide dismutase (SOD) –** converts superoxide (O_2^-) into hydrogen peroxide (H_2O_2);
- **Catalase (CAT) and peroxidase (POD) –** decompose H_2O_2 into water and oxygen;
- **Ascorbate peroxidase (APX) –** plays a key role in defense against oxidative stress;
- **Non-enzymatic compounds –** glutathione, ascorbic acid, flavonoids, carotenoids *(Ahmad, P. et al, 2022)*.

3.3. Biochemical Changes Specific to Salinity Stress

In saline soils, chickpea responses include:

- **Exclusion of toxic ions (Na^+ and Cl^-)** from aerial tissues;
- **Maintenance of a favorable K^+/Na^+** ratio in meristematic cells;
- **Deposition of lignin and callose** in cell walls to limit the entry of harmful ions;
- **Increase in proline content** and reduction of osmotic stress *(Negusse, H. et al, 2025)*.

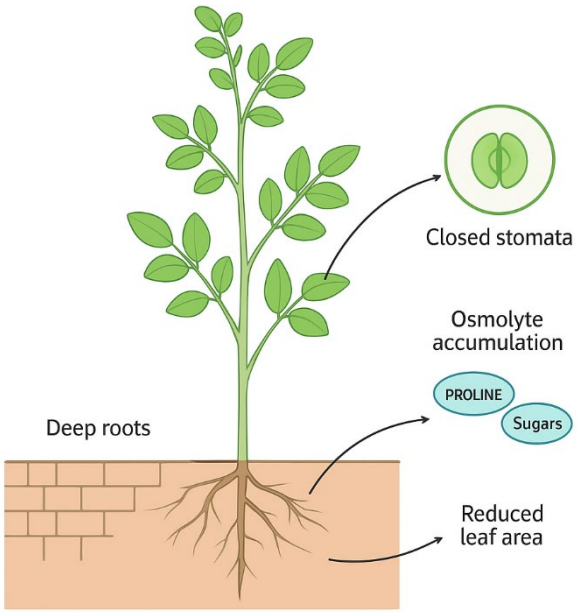

Fig. 3 - Physiological responses of chickpea to drought stress

3.4. Hormonal Responses

Plant hormones regulate numerous adaptive responses:

- **Abscisic acid (ABA) –** increases during drought and salinity; induces stomatal closure and expression of tolerance-related genes;
- **Salicylic acid (SA) and jasmonate (JA) –** involved in defense against pathogens;
- **Ethylene –** regulates senescence and activation of stress responses;
- **Auxins and cytokinins –** influence growth and developmental balance under stress.

3.5. Gene Expression and Stress Proteins

Chickpea copes with stress through regulation of gene expression:

- **LEA proteins (Late Embryogenesis Abundant) –** stabilize membranes and proteins during dehydration;
- **Heat shock proteins (HSPs) –** protect enzymes and cellular structures under high temperatures;
- **Transcription factors (TFs) –** such as DREB, MYB, NAC, WRKY – regulate the stress response cascade *(Soren, K. R. et al, 2021)*.

3.6. Morphological Adaptations

- **Leaf pubescence –** reflects excessive solar radiation;
- **Thick and waxy cuticle –** reduces water evaporation;
- **Reduced leaf angle –** minimizes overheating.

RESULTS

4.1. Impact of Biotic and Abiotic Stresses on Chickpea Productivity

Biotic stresses (diseases, pests) and abiotic stresses (drought, salinity, heat, acidic soils) significantly reduce the production potential of chickpea, affecting all stages of plant development, from germination to seed formation. Vascular wilt caused by *Fusarium oxysporum* f. sp. *ciceris* and Ascochyta blight remain the most frequent and severe diseases, causing yield losses of up to 80% under unfavorable

conditions *(Varshney, R. K. et al, 2019)*. Pests such as *Helicoverpa armigera* further reduce yield by damaging pods and developing seeds.

Abiotic stresses, particularly water deficit and salinity, directly influence photosynthetic processes, nutrient uptake, and cellular metabolism. The relative impact of major abiotic and biotic stresses on chickpea yield is illustrated in Figure 4. In semi-arid regions, terminal drought particularly affects the reproductive stages, severely impacting pod number and size *(Kashiwagi, J. et al, 2006)*. Salinity limits plant growth through ion toxicity and osmotic stress, disrupting ionic balance and enzymatic processes *(Negusse, H. et al, 2025)*.

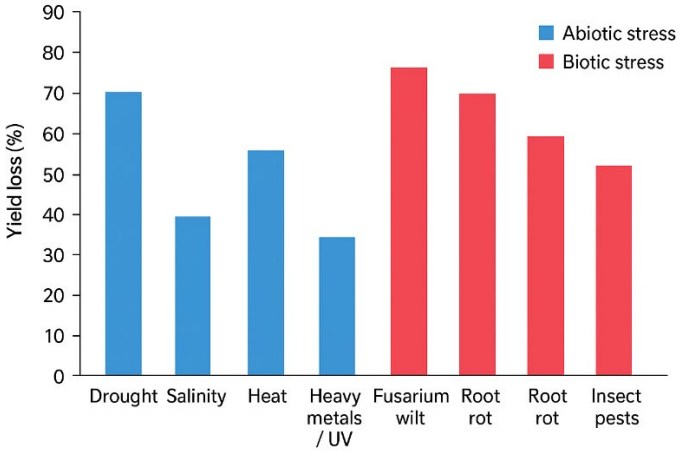

Fig. 4 - Impact of Major Abiotic and Biotic Stresses on Chickpea Yield

4.2. Adaptive Mechanisms of Chickpea to Stress

Chickpea plants have developed a range of physiological and biochemical responses to counteract stress effects:

- **Drought adaptations:** deep roots, osmolyte accumulation, stomatal closure, and morphological modifications (cuticle, leaf pubescence) *(Kashiwagi, J. et al, 2006)*.
- **Oxidative stress management:** activation of antioxidant systems (SOD, CAT, APX), synthesis of phenolic compounds and other antioxidants *(Ahmad, P. et al, 2022)*.
- **Hormonal responses:** increased ABA levels to regulate stomatal closure and stress-related gene expression, involvement of SA and JA in defense against pathogens *(Soren, K. R. et al, 2021)*.
- **Stress protein expression:** LEA proteins and HSPs that stabilize cellular structures under dehydration and high-temperature conditions.

These mechanisms are interconnected, providing multifactorial tolerance that varies among genotypes. The adaptive responses of chickpea under combined biotic and abiotic stresses are summarized in Figure 5.

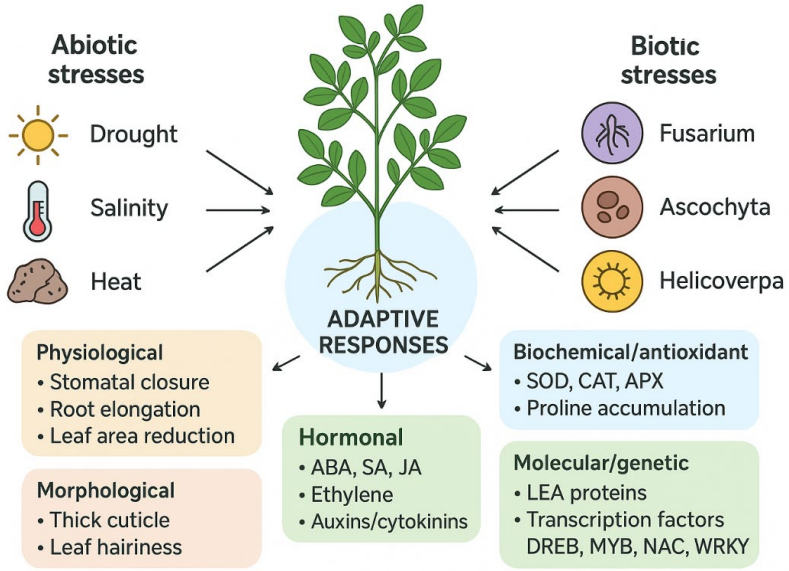

Fig. 5 - Integrated Adaptive Mechanisms of Chickpea under Combined Biotic and Abiotic Stresses

4.3. Modern Breeding and Management Strategies

Technological advances have enabled the integration of effective strategies to enhance chickpea resilience:

- **Marker-assisted breeding:** identification of genes and QTLs associated with tolerance to multiple stresses facilitates rapid and precise selection *(Varshney, R. K. et al, 2019)*.
- **Utilization of local and wild genetic resources:** the genetic diversity of landraces and related species is exploited to introduce stress-tolerance traits *(Negusse, H. et al, 2025)*.
- **Integrated agronomic practices:** crop rotation, targeted fungicide applications, optimized irrigation and fertilization improve plant stress responses.
- **Emerging biotechnologies:** genome editing (e.g., CRISPR-Cas9) and the use of beneficial microorganisms (rhizobacteria, mycorrhizae) are at the experimental stage but offer promising sustainable solutions.

4.4. Challenges and Perspectives

Despite significant progress, major challenges remain:

- **Genetic complexity of multifactorial tolerance:** requires holistic and collaborative approaches among geneticists, physiologists, and agronomists.
- **Impact of climate change:** may exacerbate simultaneous multiple stresses, necessitating the development of cultivars with broad resilience.
- **Adoption of innovative technologies:** remains limited in vulnerable regions due to costs and infrastructure constraints.

CONCLUSIONS

Chickpea (Cicer arietinum L.) is a crucial legume crop for global food security due to its high nutritional value and important role in sustainable agricultural systems. However, its productivity is severely constrained by a wide range of biotic and abiotic stresses, which directly affect plant development and yield.

Biotic stresses, such as fungal diseases and pest attacks, continue to cause significant losses, while **abiotic factors**—drought, salinity, extreme temperatures, and unfavorable soil conditions—impose constant pressure on chickpea's adaptive capacity.

Chickpea's **physiological and biochemical responses** to these stresses are complex and involve stomatal regulation, accumulation of osmoprotective compounds, activation of antioxidant systems, and modulation of gene expression. Understanding these mechanisms is essential for developing effective breeding strategies.

Advances in **molecular genetics, biotechnology, and agronomic management** provide tangible opportunities to enhance chickpea resilience to multiple stresses. Additionally, leveraging existing **genetic diversity**, combined with modern selection methods, can lead to high-performing cultivars adapted to changing climatic conditions.

Nonetheless, long-term success requires an **integrated approach**, combining fundamental research with practical applications, fostering multidisciplinary collaborations, and implementing supportive policies for the adoption of new agricultural technologies.

Thus, ensuring **stable and sustainable chickpea production** under both biotic and abiotic stress conditions represents a major challenge, but also a significant opportunity for research and innovation in agriculture.

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TECHNOLOGIES IN THE DEHYDRATION OF BERRIES: A REVIEW
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TEHNOLOGII ÎN DESHIDRATAREA FRUCTELOR DE PĂDURE

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ABSTRACT
The food industry is a complex industry with a number of specific characteristics related to both the nature of the raw materials processed and the finished products obtained. The raw materials used in the food industry are biological products (mostly of animal and vegetable origin), degradable and it should also be noted that agricultural production is seasonal (it takes place at certain times of the year). Fruits and vegetables play a significant role in the human diet due to their abundance of beneficial chemicals. Among the fruits, berries are widely appreciated and recognized as valuable sources of nutrients and bioactive compounds, including minerals, phenolic compounds (especially anthocyanins), and vitamins. The preservation of vegetables and fruits is an essential component of the modern food industry, playing a major role in ensuring their availability throughout the year and reducing food waste. This article presents the current state in the field of dehydration of berries, including both traditional and modern methods, as well as the various technological combinations used in the dehydration process.

REZUMAT
Industria alimentară este o industrie complexă, cu o serie de caracteristici specifice legate atât de natura materiilor prime prelucrate, cât și de produsele finite obținute. Materiile prime utilizate în industria alimentară sunt produse biologice (în principal de origine animală și vegetală), degradabile, și trebuie menționat faptul că producția agricolă este sezonieră (are loc în anumite perioade ale anului). Fructele și legumele joacă un rol semnificativ în dieta umană datorită abundenței lor de substanțe chimice benefice. Din categoria fructelor, fructele de pădure sunt foarte apreciate și recunoscute ca surse valoroase de nutrienți și compuși bioactivi, inclusiv minerale, compuși fenolici (în special antocianine) și vitamine. Conservarea legumelor și fructelor este o componentă esențială a industriei alimentare moderne, jucând un rol major în asigurarea disponibilității acestora pe tot parcursul anului și în reducerea risipei alimentare. Acest articol prezintă stadiul actual în domeniul deshidratării fructelor de pădure, incluzând atât metodele tradiționale, cât și cele moderne, precum și diversele combinații tehnologice utilizate în procesul de deshidratare.

INTRODUCTION
The fast population growth has significantly increased the global demand for food. While the Green Revolution and the rise of food industrialization technologies have greatly contributed to addressing this need, a substantial gap between supply and demand still persists. In addition, the increased focus on human health has made consumers more conscious of the need to achieve rich in nutrients products and the importance of food safety and quality in preventing chronic illnesses. As a result, drying technologies have shown significant and rapid developments in order to preserve high-quality food products *(Ibrahim, A. et al, 2023)*.

The food industry is a complex industry with a number of specific characteristics related to both the nature of the raw materials processed and the finished products obtained. The raw materials used in the food industry are biological products (mostly of animal and vegetable origin), degradable and it should also be noted that agricultural production is seasonal (it takes place at certain times of the year).

Fruits and vegetables play a significant role in the human diet due to their abundance of beneficial chemicals *(Nowacka, M. et al, 2021)*. The World Health Organization recommends that we should consume minimum 400 grams of fruits and vegetables each day, in order to maintain the proper functioning of our organism. In addition to preventing undernutrition, a varied and well-balanced diet also helps protect the body against different illnesses *(World Health Organization: WHO, 2013; Bondonno, N.P. et al, 2017).*

The term "berry" is commonly used to refer to a small fruit that can be eaten whole. Botanically, however, it is defined as a type of fleshy fruit resulting from the development of the ovary of a single flower into an edible pericarp. Regardless of the definition, berries are widely appreciated and recognized as valuable sources of nutrients and bioactive compounds, including minerals, phenolic compounds (especially anthocyanins), and vitamins. Anthocyanins are natural pigments belonging to the flavonoid class, responsible for the red, purple, and blue colors characteristic of the berries. In addition to their chromatic role, these compounds have been associated with multiple health benefits due to their antioxidant and anti-inflammatory properties. Fruits such as berries are important sources of nutrients essential for maintaining health, but they are highly perishable. Their characteristics are influenced by a number of factors, such as cultivation methods, geographical region, storage conditions, stage of maturity, and climatic conditions. These factors can cause significant changes in fruit quality, affecting their bioactive compound content and antioxidant capacity. In this context, the implementation of advanced and appropriate post-harvest processing technologies is essential to reduce quantitative and qualitative losses, thus preventing undesirable alterations in weight, color, texture, and aromatic profile *(Pateiro, M. et al, 2022).*

The preservation of vegetables and fruits is an essential component of the modern food industry, playing a major role in ensuring their availability throughout the year and reducing food waste. Microorganisms that act on agri-food products contribute most to their qualitative deterioration. Therefore, the purpose of preservation techniques is to inhibit or destroy the enzymes and microorganisms found in these products *(Radojčin, M. et al, 2021; Ramaj, I. et al, 2021).* Among the most commonly used preservation methods, drying occupies an important place due to its efficiency in reducing water content, which inhibits microbiological activity and unwanted biochemical reactions (*Nowacka, M. et al, 2023)*.

This article presents the current state in the field of dehydration of berries, including both traditional and modern methods, as well as the various technological combinations used in the dehydration process.

PRINCIPLES OF DEHYDRATION AND ITS ROLE IN PRESERVATION

Food preservation, with the aim of extending shelf life while maintaining safety and quality, is a major concern in the food industry. In this context, new preservation techniques have been constantly developed, as well as strategies for integrating them with modern technologies. The food preservation process involves the application of treatments and handling methods designed to stop or significantly slow down the degradation of products, whether in terms of loss of quality, edibility, or nutritional value, which is often caused or accelerated by the action of microorganisms.

Typically, preservation involves inhibiting the growth of bacteria, fungi, and other harmful microorganisms, as well as reducing the oxidative processes of lipids, which are responsible for rancidity. At the same time, preservation aims to slow down natural aging processes and discoloration phenomena, such as the enzymatic browning observed in freshly cut apples *(Yadav, A.K. et al, 2014)*.

Dehydrating vegetables and fruits is a complex technological process that reduces the natural water content to a level that prevents the activity of microorganisms without destroying the tissues or depreciating the nutritional value of the products being dehydrated. The evaporation of water from vegetables and fruits is a complex process involving both their anatomical structure and the permeability of their cell membranes *(Ilie, D.M. et al, 2020)*.

When refer to water loss, a number of interchangeable words can be used, including drying, dehydration, and withering. But it's important to recognize that there are some differences between them. Therefore, dehydration is a controlled process of water loss using artificially produced heat; drying is the process of intense water loss from products after harvest, generally conducted outdoors, using the solar energy; and withering is the results of an extended dehydration process that involves water loss and product senescence (*Mencarelli, F. et al, 2020)*.

There are various drying solutions, from the most conventional to the most innovative. Conventional drying methods are often used due to their simplicity and low costs. The high temperatures involved in these methods can negatively affect the product's final quality, leading to significant vitamin losses, color changes, and modification of flavor and texture. In the present, drying techniques have been created using the newest technologies in order to reduce the negative effects produced on by biochemical changes that affect nutritional content during drying process *(Ibrahim, A. et al, 2023).*

The most important conventional drying methods (convective drying, freeze-drying, intermittent drying, osmotic dehydration and spray drying), emerging drying techniques (electromagnetic radiation,

explosion puffing, heat pump, low-pressure superheated steam) and combined drying methods for dehydration of berries are presented in this study.

Conventional methods

The most widespread conventional drying method is **hot air drying**. During this process, the surface of the materials is exposed to a flow of hot air, and heat transfer occurs from the outside to the inside of the product. Water evaporation on the surface occurs at a faster rate than moisture diffusion from the inside to the surface, due to rapid drying on the outside and uneven heat distribution inside the materials. In general, products are subjected to high temperatures for extended periods of time in the hot air dryer. Prolonged exposure to hot air promotes the occurrence of browning reactions, both enzymatic and non-enzymatic, thus affecting the final quality of the dried product (*Mitra, P. et al, 2013)*.

Convective drying can be classified into three distinct methods: hot air drying, in which the product is directly exposed to a stream of hot air; multi-flash convective drying, characterized by intensified heat transfer due to the significant difference between the product temperature and the hot air temperature; and fluidized bed drying, where hot air is directed at a controlled speed toward the layer of product on the drying belt, ensuring uniform heat distribution and increased process efficiency *(Pateiro, M. et al, 2022)*.

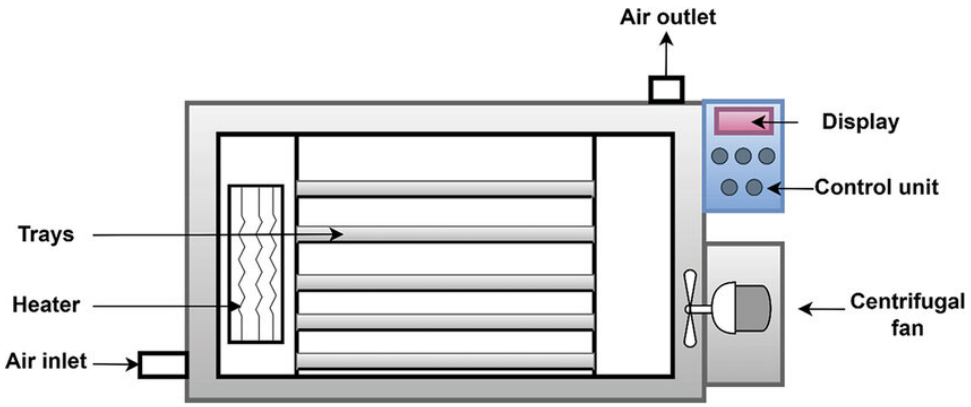

Fig. 1 - Schematic diagram of convective hot air dryer

(Kalsi, B.S. et al, 2023)

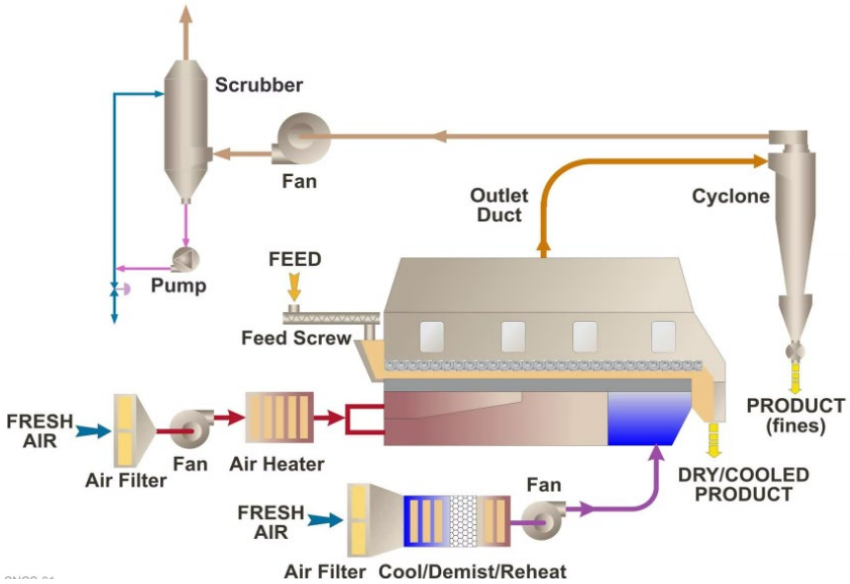

Fig. 2 - Fluidized bed dryer

(Fluid Bed Dryer, 2025)

Convective dehydration offers a number of advantages, including operational simplicity, low implementation and operating costs, and the possibility of extending the shelf life of dehydrated food products. However, this method also has a number of disadvantages, mainly due to the parameters of the drying gas (such as high temperature and relative humidity) and the long duration of the process. These

conditions can lead to the formation of a crust on the surface of the product, the degradation of heat-sensitive compounds, the occurrence of enzymatic and non-enzymatic browning reactions, the development of an undesirable taste, and visible shrinkage of the product caused by mechanical stress, which leads to reduced rehydration capacity and a decrease in the nutritional value of the final product *(Zielinska, M. et al, 2018)*.

Studies realized on berries proves that intermediate drying conditions (65 °C for 20 h) allowed to preserve the color, the polyphenol content, and the antioxidant activity of the berries *(Bustos, M.C. et al, 2018)*. Similarly, it was found that applying a drying regime characterized by high temperatures and short times (50°C for 5 days) compared to versions with lower temperatures and longer times (40°C for 12 days and 30°C for 30 days, respectively) enhanced the accumulation of fructose, glucose, and total soluble sugars. This regime also led to an increase in the concentration of organic acids, such as citric acid, malic acid, lactic acid, tartaric acid, and gallic acid, along with their derivatives, in the composition of the grape berries *(Chen, K. et al, 2021)*.

Vacuum drying is carried out at low temperatures, making it a suitable method for dehydrating heat-sensitive materials. This technique allows for superior retention of nutrients and volatile compounds in dried products, thus helping to maintain nutritional and sensory quality. However, the applicability of vacuum drying is limited by the high costs associated with the process, as well as the length of time required for drying (*Mitra, P. et al, 2013)*.

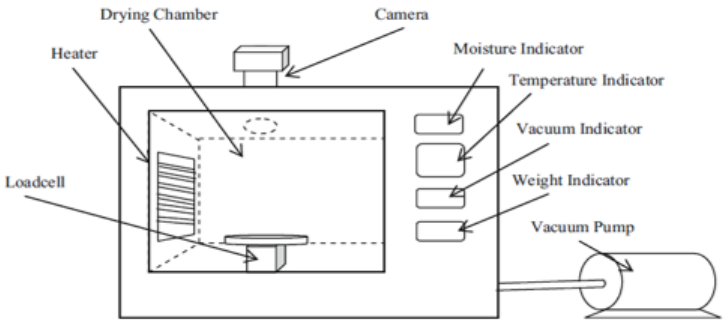

Fig. 3 - Schematic diagram of vacuum drying system
(Pourfarzad, A. et al, 2015)

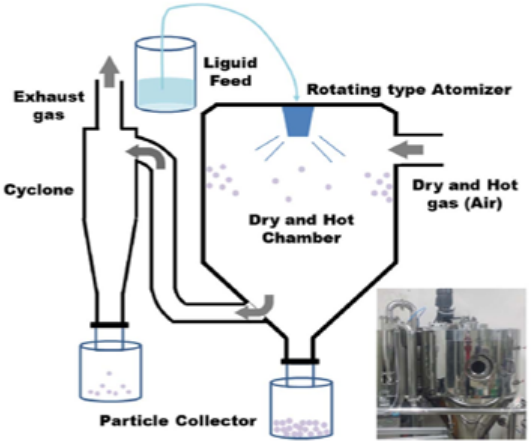

Fig. 4 - Schematic illustration of spray dryer
(Choi, Y.H. et al, 2016)

The evaluation of the vacuum drying process applied to wild berries (such as blackberries, raspberries, red currants, and strawberries) under various experimental conditions showed that increasing the temperature reduces the drying time but has a negative impact on the quality of the final product. On the other hand, an increase in residual pressure during drying leads to a longer process duration *(Ermolaev, V.A., 2018)*.

When murta berries subjected to vacuum drying at different temperatures, the result was a microbiologically safe product (a_w < 0.500). A different behaviour was observed between the free and bound forms of the total phenolic compound (TPC) and total flavonoid (TFC) content. In general, vacuum drying led to a decrease in TPC and TFC content compared to fresh murta berries. The highest levels of free forms of the compounds analyzed in dried fruits were recorded at 90°C (2373.21 mg GAE/g d.m. for TPC and 854.3 mg QE/g d.m. for TFC). In addition, dried samples of murta berries had higher bound flavonoid contents than the fresh samples *(López, J. et al, 2017)*.

Spray drying (SD) is a well-established industrial technology widely used for processing heat-sensitive materials in liquid food compositions. The main purpose of this method is to quickly remove the liquid phase, minimizing the negative impact on the quality of the final product, while reducing capital and operating costs and avoiding adverse effects on the environment. By applying heat, SD enables the efficient conversion of a diluted fluid suspension into a high-quality dry powder.

The process involves four fundamental steps: atomization of the liquid, contact of the atomized droplets with a hot gas stream, evaporation of the water content, and separation of the solid phase (powder) from the residual gas *(Sagar, V.R. et al, 2010)*. Experiments realized with berry extract dried through spray drying method conducted to the obtaining of a powder with good solubility and dispersibility. The dried fruits

obtained are characterized by superior quality, highlighted by their uniform size and shape, as well as low water activity (a_w) and moisture content values. In addition, high glass transition temperature (T_g) values contribute to the physical and chemical stability of the product, ensuring an extended shelf life *(Pateiro, M. et al, 2022).*

This method has limitations associated with the use of high temperatures, which can lead to the degradation and loss of valuable bioactive compounds; depositions on the wall caused by organic acids and low molecular weight sugars from the juice; the size of equipment and the installation costs *(Qi, Y. et al, 2021; Calín-Sánchez, Á. et al, 2015).*

Freeze-drying (lyophilization or cryodesiccation) is one of the most effective drying methods used to preserve the quality of dehydrated food products. However, its commercial application, especially for fruit, involves high costs. The freeze-drying process takes place at very low temperatures, at which the solid state (frozen) of water from the fruit is removed by sublimation, meaning that it passes directly into a gaseous state without reaching the liquid phase. This low drying temperature, together with the absence of liquid water during the process, contributes to a significant slowdown in biochemical reactions and the development of microorganisms. At the same time, keeping the water in solid form allows the primary structure and initial shape of the product to be maintained, with minimal reduction in volume (*Mitra, P. et al, 2013).*

This technique causes minimal structural shrinkage and allows for the effective preservation of the natural color and flavor of berries, while ensuring a high rehydration rate and maintaining the specific taste characteristics of fresh fruit. Freeze-drying is one of the gentlest methods of dehydration, allowing for the production of high-quality products in which volatile compounds, bioactive compounds, and vitamins are preserved in significant proportions. The disadvantages of this method is represented by the pre-treatment stage (initial freezing), vacuum equipment, installation costs and high energy consumption *(Pateiro, M. et al, 2022).*

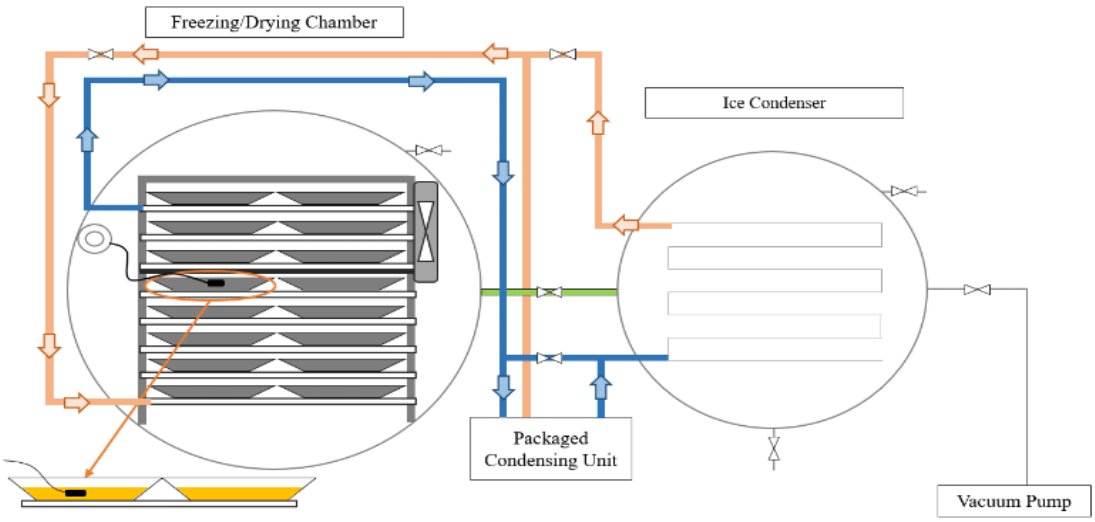

Fig. 5 - Freeze/drying equipment
(Mawilai, P et al, 2019)

Osmotic dehydration is a process whereby water is transferred from a medium with a lower solute concentration to one with a higher concentration, through a semipermeable membrane, until an osmotic equilibrium is reached between the two media.

This method is widely used in food preservation, as it helps reduce water activity in fruits and vegetables, thereby limiting the growth of microorganisms and spoilage reactions. Compared to other preservation techniques, osmotic dehydration is often preferred due to its ability to maintain the color, flavor, nutritional properties, and volatile aromatic compounds of the treated products *(Yadav, A.K. et al, 2014).*

The application of osmotic dehydration in strawberries, using sucrose as the reference osmotic solution was investigated. In addition, inulin and aronia juice concentrate were analyzed as potential carriers of functional compounds, being used as partial substitutes for sucrose. All solutions used had a 50°Brix concentration and were applied in the temperature range of 30–50°C for 360 minutes. Both inulin and aronia juice concentrate favored mass exchange during the process. In the case of inulin, a lower increase in solid mass was observed compared to sucrose (1.29 vs. 1.48 – normalized dry matter content in osmotically

dehydrated strawberries), a phenomenon explained by the limited ability of inulin to penetrate tissue structures. On the other hand, the use of juice concentrate led to an increase in polyphenol content and, implicitly, to an intensification of the antioxidant activity of the final product *(Kowalska, H. et al, 2017).*

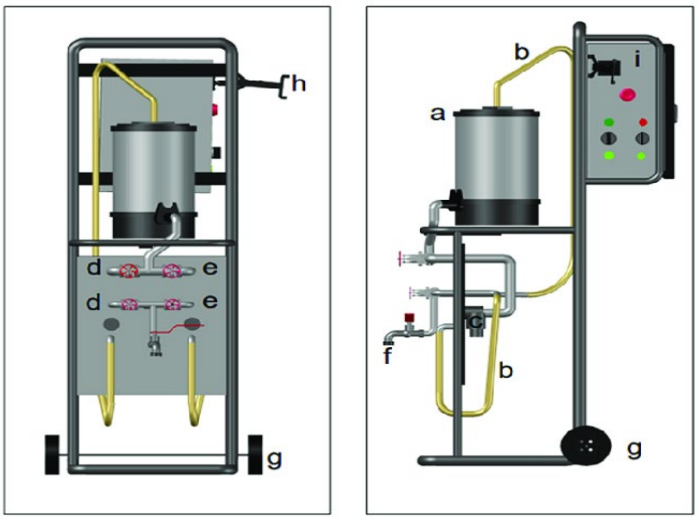

Fig. 6 - Osmotic dehydration equipment

(Flores-Mendoza, L. et al, 2023)

a. osmodehydrator tank; b. recirculation hose; c. water pumps; d. stopcocks for pump 1; e. stopcocks for pump 2; f. drain valve; g. wheels; h. tablet holder; i. control box

Emerging technologies

In order to avoid the negative effects that overcome from the berries dehydrating through conventional methods, the food industry adopted new technologies or modified existing ones.

The heat pump dryer was developed to recover sensible and latent heat, which is typically wasted in other drying methods. In this system, the dehydration process takes place by condensing air in a compression evaporator, which allows a flow of hot, dry air to be supplied to the product being dried. The latent heat of vaporization is recovered from condensation and reused to reheat the drying air. This technology represents an advanced version of the convection dryer equipped with a refrigeration system *(Pateiro, M. et al, 2022).* The advantages of heat pump drying is the reduction in processing time and temperatures involved, compared to conventional hot air drying. Under these conditions, samples dried using this method exhibit superior overall quality. In addition, drying times are reduced by approximately 20%, and operating costs are reduced by up to 19% *(Zhao D. et al, 2016).*

In the category of **electromagnetic radiation** drying methods used for berries, it can be included the microwave, infrared, refractance window and radio frequency.

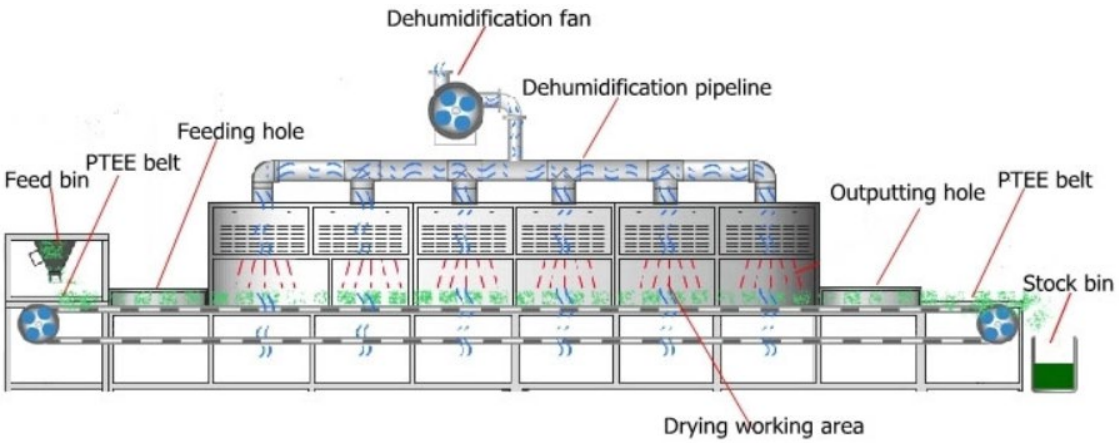

Fig. 7 - Continuous microwave drying machine

(Microwave food drying machine, 2025)

One of the most used drying methods for berries is the ***microwave drying*** because of the following advantages: obtaining of high-quality products, reduced costs and heating time, increased energy efficiency.

This method involves the transmission of electromagnetic waves in the spectrum between 1 mm and 1 m, corresponding to frequencies of 915 and 2450 MHz, through which thermal energy is generated as a result of induced molecular vibration. The oscillations of the molecules in the berries structure cause the production of the heat necessary for the dehydration process *(Kumar, C. et al, 2019).*

The disadvantages of this method are the rapid increase in the internal temperature of the berries (which causes significant degradation of thermolabile bioactive compounds) and uneven heating of the product *(Sun, Y. et al, 2019).*

Another electromagnetic radiation drying method used in the case of berries is the ***infrared drying method***. This technology involves the use of simple equipment, reduced drying times, and lower energy consumption, thus leading to a higher quality product with lower production costs. The infrared drying method ensures the uniform and constant transfer of thermal energy from the heat source to the berries, in the form of electromagnetic waves with wavelengths between 0.75 and 1000 μm.

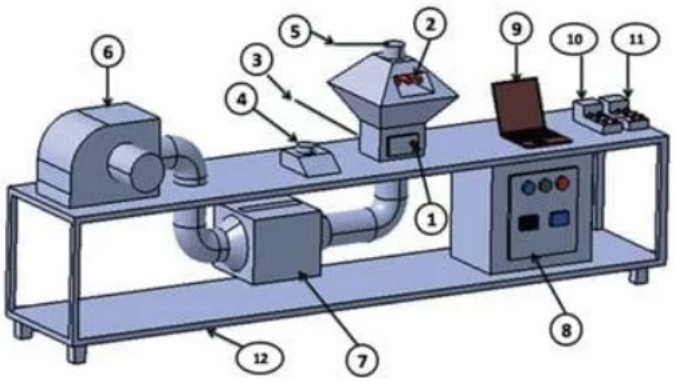

Fig. 8 - Infrared dryer schema

(Infrared Dryers: Working Principles, Design, and Applications, 2024)

1. drying chamber; 2. lamp infrared; 3. air temperature sensor; 4. precision balances; 5. air velocity sensor; 6. fan and electrical motor; 7. electrical heater; 8. inverter and thermostat; 9. computer; 10. thermometer; 11. psychrometer; 12. chassis.

Another emerging technology used for the dehydration of berries is represented by the **explosion puffing drying method**. This is an efficient technology which contain the following main components: steam generator, decompression valve, vacuum chamber, puffing chamber, vacuum pump, and air compressor. Along the process, the berries are puffed for 5 min at 80–130 °C while the pressure is 0.1–0.3 MPa. After that, the berries are vacuum-dried for 180 minutes at 50–70 °C to determine their ultimate moisture content *(Xiaoping, F. et al, 2018).* When the fruit's bounded water evaporates, the product expands as a result of a rapid decrease in pressure and/or rise in temperature, changing the berries internal structure into a more permeable structure. The advantage of this drying method is the preservation of majority of the berry's nutrients, but some nutrients could be affected by the high temperatures achieved in the vacuum-drying phase. In order to save processing time and energy, this method is typically used as an intermediate drying phase alongside with other strategies (such as convective drying and freeze-drying).

Superheated steam drying (SS) occurs in the absence of air, in an environment consisting exclusively of steam. The efficiency of this method in drying food products is due to the supply of sensible heat, which allows the product temperature to rise above the saturation temperature corresponding to the applied pressure. The resulting vapors only need to be evacuated when the pressure exceeds a preset limit, at which point the excess steam is removed. A major advantage of this process is the possibility of recycling the drying cycle, provided that sensitive heat is continuously supplemented. In addition, most conventional convection or conduction drying equipment can be easily adapted to operate on superheated steam (*Sagar, V.R. et al, 2010).*

One of the most energy-efficient techniques for fruit dehydration is **intermittent drying**, which alternates periods of effective drying with tempering times by adjusting certain of the drying process's parameters. Among the variables that may modify over time are drying air temperature, airflow rate, humidity, pressure, and/or energy intake (such as convection, conduction, radiation, and microwave). Thus, drying agents such as hot air, vacuum, microwave power, infrared, or ultrasound can be employed *(Duc Pham, N. et al, 2019).* The intermittent drying process involves the reduction of products overheating (due to the repetition of the process) and the decrease of heating times. Thus, oxidative and enzymatic processes

are reduced, meaning that the heat-sensitive bioactive compounds will be protected. Unwanted effects are thereby minimized, preserving the dried berries' qualities (such as color and texture) and lengthening their shelf life *(Kumar, C. et al, 2014).*

Combined drying methods for dehydration

One of the combined drying methods used for the dehydration of berries is represented by the **microwave-convective drying.** This technique reduces the disadvantages from the convective drying, related to the heat transfer. Thus, the hot air decrease the unbound moisture presented at the product surface, while the microwave decrease the bound moisture presented at the product interior *(Kumar, C. et al, 2019).*

Microwave drying combined with vacuum contributes to improving the sensory characteristics of dehydrated products, such as color, texture, aroma, and nutrient retention, due to efficient volumetric heating and reduced drying time. In addition, the application of vacuum allows the drying temperature to be lowered by reducing the boiling point of water, which optimizes the dehydration process and reduces thermal degradation of the product (*Mitra, P. et al, 2013).*

In order to obtain a better quality products with lower energy consumption and cost, the **convective and vacuum-microwave drying** methods can be used for berries. The process takes place in two stages, first stage is represented by the convective drying, followed by the vacuum –microwave drying. Also, the convective drying can be replaced with the fluidized bed drying and followed by the vacuum –microwave drying. When this combined methods are used, microwaves contribute to a significant reduction in drying time, while the fluidization mechanism ensures uniform heat distribution throughout the product mass, leading to more homogeneous drying and reducing the risk of overheating or localized burning (*Sagar, V.R. et al, 2010).* All this will resulting in higher-quality and lower-moisture products, but the disadvantage derived from the use of those methods is represented by the substantial costs *(Sivakumar, R. et al, 2016).*

Another combined method is the **fluidized-bed drying with far-infrared assistance** which increase the temperature of fruits using wavelengths that cause the molecules to vibrate. Through this method the product quality is more efficiently controlled. An improved method for drying fruits that are heat-sensitive is represented by the **ultrasound-assisted hot air drying**, an energy-efficient and low-cost process, which produces dried products with high quality. Due to the improved process conditions (30–70 ◦C temperature for 0.5–5 minutes), the fruit experiences less adverse consequences such color darkening, cracking, shrinkage, and nutritional losses *(Rodríguez, Ó. et al, 2018).*

The swell drying is a special technique for dehydrating fruit that involves instant regulated pressure drop (DIC) drying with convective drying. This technology is done by exposing the fruit to a fast pressure decrease ($\Delta P/\Delta t > 0.5$ MPa/s) towards of a vacuum (about 4.5 kPa). Thermomechanical processes (such as expansion and immediate cooling) brought on by these pressure drops accelerate the drying process. Furthermore, the performance of the drying process, the quality of functional foods, and the sensory qualities (colour, flavor, aroma, texture) are enhanced by the brief (less than a minute) application of high pressures (0.1–1 MPa) and temperatures (80–200 °C). In this sense, compared to traditional drying processes, the enlarged structure lowers energy consumption and costs for production, prevents the shrinkage and structural collapse of dried fruits, while enabling microbial decontamination and the preservation of bioactive chemicals *(Téllez-Pérez, C. et al, 2020).*

CONCLUSIONS

The preservation of vegetables and fruits is a crucial component of the modern food industry since it helps to reduce food waste. Drying process occupies an important place among the preservation methods. The selection of the appropriate dehydration method is important for obtaining a good quality dried berries with functional properties. Recent studies showed that emerging dehydration techniques presents important advantages compared to conventional methods (such as obtaining high-quality products, energy efficiency, and minimization of temperatures and times of processing). Furthermore, each of these strategies has advantages and disadvantages, thus combining them can maximize their advantages on the preservation of berries.

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DESIGN AND SIMULATION OF A RANDOM FOREST-BASED CONTROL ALGORITHM FOR GREENHOUSE MANAGEMENT

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PROIECTAREA ȘI SIMULAREA UNUI ALGORITM DE CONTROL BAZAT PE RANDOM FOREST PENTRU MANAGEMENTUL SERELOR

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ABSTRACT

Greenhouse cultivation requires efficient control of irrigation, ventilation, and shading to ensure optimal crop growth while reducing water and energy consumption. Conventional rule-based systems rely on fixed thresholds, which lack adaptability to dynamic environmental conditions. This paper presents the design and simulation of a Random Forest (RF)-based intelligent control algorithm integrated with a Wireless Sensor Network (WSN) for greenhouse management. The simulation framework considered two wireless sensor nodes monitoring soil temperature, air temperature, soil moisture, air humidity, CO_2 concentration, and light intensity, and one actuator node controlling irrigation valves, ventilation fans, and shading screens. A dataset of 5,000 synthetic records was generated based on ranges observed in previous greenhouse experiments, with Gaussian noise added to reflect sensor uncertainty. Baseline control decisions were simulated using fixed threshold rules, while the RF model was trained in Python with 500 trees and a maximum depth of 15. Results of the simulation showed that RF outperformed the simulated baseline, achieving an average accuracy of 93.8% compared to 85% baseline algorithm. Feature importance analysis confirmed the dominant influence of soil moisture, air temperature, and light intensity.

REZUMAT

Cultura în spații protejate necesită un control eficient al irigației, ventilației și umbririi pentru a asigura o creștere optimă a plantelor și, în același timp, pentru a reduce consumul de apă și energie. Sistemele convenționale bazate pe reguli fixe nu pot răspunde adaptiv la variabilitatea condițiilor de mediu. Această lucrare prezintă proiectarea și simularea unui algoritm inteligent de control bazat pe Random Forest (RF), integrat într-o rețea de senzori wireless (WSN), *pentru managementul microclimatului din seră. Cadrul de simulare a considerat două noduri de senzori wireless pentru monitorizarea temperaturii solului și aerului, umidității solului și aerului, concentrației de CO_2 și intensității luminoase, precum și un nod actuator pentru controlul irigației, ventilației și umbririi. A fost generat un set de date sintetice de 5.000 de înregistrări pe baza intervalelor observate în experimente anterioare în sere, la care s-a adăugat zgomot gaussian pentru a reflecta incertitudinea senzorilor. Deciziile baseline au fost simulate pe baza unor reguli cu praguri fixe, iar modelul RF a fost antrenat în Python cu 500 de arbori și o adâncime maximă de 15. Rezultatele simulării au arătat că RF a depășit baseline-ul simulat, obținând o acuratețe medie de 93,8% comparativ cu 85% a algoritmului de bază. Analiza importanței caracteristicilor a confirmat rolul dominant al umidității solului, temperaturii aerului și intensității luminoase.*

INTRODUCTION

Modern agriculture is under increasing pressure to improve yield and quality, while reducing input costs and environmental impact. Greenhouse cultivation represents a controlled-environment agriculture paradigm where microclimate parameters (temperature, humidity, light, soil moisture) can be regulated to favor plant development and better yields.

However, without intelligent control, greenhouses may consume excessive amounts of water and energy or expose plants to suboptimal conditions *(Soussi et al., 2025).*

Wireless Sensor Networks (WSNs) have emerged as a key enabling technology, allowing real-time monitoring and control of environmental variables inside greenhouses. These networks provide continuous data on temperature, humidity, soil moisture, and solar radiation, which can be used to drive control actions such as irrigation, ventilation, and shading *(Dhanaraju et al., 2022).* While many greenhouse control systems are based on fixed thresholds or simple rule-based logic, these approaches lack flexibility and adaptability to changing environmental conditions.

Machine learning (ML) offers a promising alternative, providing adaptive and data-driven decision making *(Venkataramanan et al., 2025).* Techniques such as Random Forest (RF) are particularly attractive because they combine predictions from multiple decision trees, thereby helping to reduce overfitting and improve accuracy. Moreover, ML approaches are valuable for agricultural environments precisely because sensor data is often noisy or incomplete, and interpretability (e.g. via feature importance) helps in identifying key variables. *(Platero-Horcajadas et al., 2024).*

Recent studies confirm the applicability of RF algorithms in greenhouse management. For example, Tsai et al. (2020) applied Random Forest together with weather forecast data to simulate and predict soil temperature and volumetric water content in a greenhouse, and reported that RF achieved higher accuracy than traditional physical or numerical models. These findings highlight the suitability of RF for greenhouse control applications, where accurate prediction of environmental variables is essential for managing irrigation and related processes *(Tsai et al., 2020).* Another recent study by Peng et al. (2021) estimated grape sap flow under different irrigation treatments using Random Forest and Partial Least Squares models in a greenhouse.

The RF model showed higher predictive accuracy and stability than PLS, with R^2 values > 0.78 and Willmott's index of agreement > 0.90, particularly when including both meteorological factors and soil moisture content across multiple soil layers. Liu et al. (2025) evaluated Random Forest (RF), Multiple Linear Regression (MLR), Support Vector Regression (SVR), LSTM, and GRU models for multi-step prediction of solar greenhouse indoor temperature. Their results showed that while GRU achieved the highest accuracy across all time horizons, RF and SVR also performed well in short-term predictions, highlighting the relevance of RF in greenhouse climate modeling.

In this paper, we propose and evaluate the design and simulation of a Random Forest-based intelligent control algorithm for a greenhouse equipped with two wireless sensor nodes and one actuator node. The actuator controls irrigation, ventilation, and shading subsystems, with decisions generated in real time from simulated sensor data. The objectives are to maintain favorable microclimate conditions, reduce simulated water and energy consumption, and demonstrate the potential of data-driven methods compared to traditional rule-based control.

MATERIALS AND METHODS

The experimental setup was modeled after a greenhouse equipped with a Wireless Sensor Network (WSN) consisting of two sensor nodes and one actuator node, following the design presented by Săcăleanu et al. (2024). Each sensor node was built around a low-power microcontroller and a ZigBee-based communication module, ensuring reliable data transfer to the central coordinator. The integrated sensor suite measured the following environmental parameters:

- Soil temperature (°C)
- Air temperature (°C)
- Soil moisture (%)
- Air relative humidity (%)
- CO_2 concentration (ppm)
- Light intensity (lux)

The actuator node was designed to control three greenhouse subsystems: irrigation (via solenoid valves), ventilation (via exhaust fans), and shading (via motorized shading screens). Communication between sensor and actuator nodes was coordinated through a star-topology WSN, with data aggregation performed at the gateway node. The overall system architecture allowed near real-time response to changes in greenhouse microclimate *(Săcăleanu et al., 2024).*

Sensor readings were defined according to typical ranges observed in previous greenhouse experiments *(Săcăleanu et al., 2024).* Although real measurements provided the reference ranges, the dataset used in this study was synthetically generated to simulate sensor outputs. A total of 5,000 records

were produced, covering the following intervals: air temperature 18–35 °C, soil temperature 16–30 °C, air relative humidity 45–85 %, soil moisture 20–60 %, CO_2 concentration 400–1200 ppm, and light intensity 500–20,000 lux. To approximate realistic measurement conditions, Gaussian noise (σ = 2% of the measured value) was added to each parameter, reflecting sensor uncertainty reported in similar IoT deployments. In addition, missing values (up to 2% of the dataset) were artificially introduced and imputed using linear interpolation. All features were normalized to zero mean and unit variance prior to model training. Each record thus represents a simulated decision cycle, corresponding to simultaneous readings from the two sensor nodes, aggregated into a single input vector. Random Forest (RF) was selected as the intelligent control algorithm due to its robustness, accuracy, and interpretability. RF is an ensemble method that constructs a large collection of decision trees, each trained on a bootstrap sample of the dataset, with random feature selection at each split *(Breiman, 2001).* This diversity reduces overfitting and improves predictive performance compared to individual decision trees. Predictions are aggregated by majority voting for classification tasks, providing stable and accurate decisions *(Liaw and Wiener, 2002).*

In greenhouse control, RF is particularly suitable because it can handle heterogeneous data (continuous and categorical), is resilient to noisy or incomplete sensor readings, and provides feature importance rankings, which help identify the most influential parameters for control. Furthermore, RF can be implemented efficiently, making it practical for deployment in IoT-based agricultural monitoring systems.

The RF received as input the vector of environmental parameters:

$$X=\{Tair, Tsoil, RHair, Msoil, CO2, L\} \quad (1)$$

where T_{air} is air temperature (°C), T_{soil} soil temperature (°C), RH_{air} air relative humidity (%), M_{soil} soil moisture (%), CO_2 concentration (ppm), and L light intensity (lux). The output was a categorical decision vector:

$$Y=\{Irrigation, Ventilation, Shading\} \quad (2)$$

with discrete actuator states: irrigation {ON, OFF}, ventilation {ON, OFF}, and shading {OPEN, PARTIAL, CLOSED}.

Ground truth labels for training were not collected from a physical system, but were simulated using fixed threshold rules validated by agronomic expertise. These rules defined actuator states for irrigation, ventilation, and shading based on combinations of environmental parameters (e.g., irrigation ON if soil moisture < 30% and air temperature > 28 °C). The resulting actuator decisions served as the baseline control system. It is important to note that the baseline was therefore a simulated rule-based system, designed for fair comparison with the RF algorithm under identical input conditions. After training, the RF model learned nonlinear combinations of features, enabling generalization beyond deterministic threshold rules.

This design allowed the RF algorithm to translate raw microclimate data into actionable control decisions, aiming to stabilize greenhouse conditions, improve plant health, and optimize water and energy use.

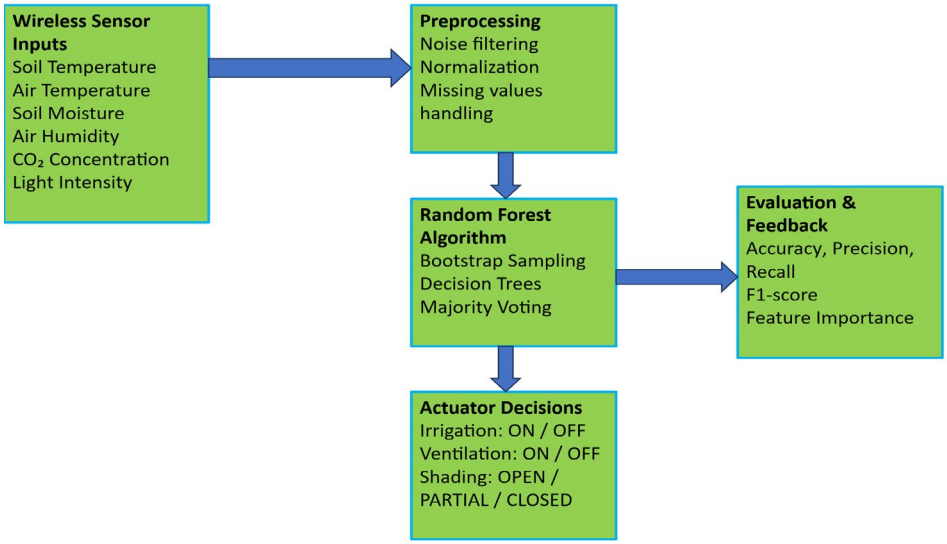

Fig. 1 - Flowchart of Random-Forest Greenhouse Control

The Random Forest (RF) algorithm was implemented and trained using the Python programming language (version 3.11) and the Scikit-learn library *(Pedregosa et al., 2011).* Python was selected for its wide adoption in data science and machine learning, availability of open-source libraries, and strong community support, making it suitable for rapid prototyping and deployment of intelligent control models in agriculture.

The two sensor nodes monitored distinct but overlapping areas of the greenhouse, and their readings were aggregated to provide a unified input vector for a single actuator node. Each of the 5,000 records in the dataset thus represents one decision cycle, combining simultaneous measurements from both sensor nodes (air temperature, soil temperature, air humidity, soil moisture, CO_2 concentration, and light intensity) into a single instance that was mapped to an actuator command (irrigation, ventilation, or shading).

The preprocessed dataset of 5,000 labeled records was divided into training (70%) and testing (30%) subsets, ensuring balanced representation of all actuator states. The RF model was configured with the following hyperparameters:

- Number of trees: 500
- Maximum depth: 15
- Minimum samples per split: 2
- Minimum samples per leaf: 1
- Splitting criterion: Gini impurity

These parameters were selected based on prior experiments in greenhouse environments and environmental IoT deployments. To prevent overfitting and ensure generalizability, fivefold cross-validation was employed, and performance metrics were averaged across folds.

Hyperparameter tuning was performed using a grid search approach. The evaluation metrics included:

- Accuracy (%): overall correct classifications of actuator states.
- Precision, Recall, and F1-score: to evaluate the model performance across different control classes (irrigation, ventilation, shading).
- Confusion matrix: to identify misclassification patterns between actuator states.

The RF model also provided feature importance values, calculated as the mean decrease in Gini impurity. These rankings allowed identification of the most relevant environmental parameters for each control decision (e.g., soil moisture as the primary driver for irrigation, air temperature for ventilation, and light intensity for shading). Such interpretability is valuable for agronomic experts when validating the system.

The trained Random Forest model was exported as a serialized object using the Python joblib package. To evaluate deployment feasibility, the model was executed on a Raspberry Pi 4 Model B (4 GB RAM) in a simulated greenhouse control environment. Incoming data packets, representing the 5,000 synthetic records, were processed at one-minute intervals, and actuator control commands were generated according to the RF predictions. While the actuator node and communication protocols were modeled based on real designs (Săcăleanu et al., 2024), the present study focused on simulation rather than physical implementation.

This approach demonstrates the practicality of deploying machine learning algorithms on low-power edge computing platforms for future real-world greenhouse applications.

RESULTS

Table 1 presents a subset of the raw input data simulated from the wireless sensor nodes, after the addition of Gaussian noise to simulate real measurement uncertainty. The dataset includes six environmental variables used as inputs for the Random Forest (RF) training process.

Table 1

Example of raw input data used for Random Forest training

Air Temperature (°C)	Soil Temperature (°C)	Air Humidity (%)	Soil Moisture (%)	CO_2 (ppm)	Light (lux)
24.08	18.13	49.13	36.18	734.95	12899.16
33.70	17.02	78.19	21.93	573.36	12807.86
29.14	28.30	47.80	24.64	489.30	11025.10
28.65	28.85	84.07	20.73	670.13	2221.49
21.06	27.42	77.07	45.97	1159.11	16772.30
…	…	…	…	…	…

The complete dataset consisted of 5,000 labelled records generated over multiple greenhouse operation cycles, covering the typical ranges of each parameter.

The RF model was trained on 70% of the dataset and evaluated on the remaining 30% using fivefold cross-validation. Table 2 summarizes the performance metrics obtained.

Table 2

Performance metrics of Random Forest training.

Metric	Irrigation	Ventilation	Shading	Average
Accuracy (%)	95.1	93.4	92.8	93.8
Precision (%)	94.7	92.1	91.3	92.7
Recall (%)	95.6	93.0	92.1	93.6
F1-score (%)	95.1	92.5	91.7	93.1

The confusion matrix indicated that the model was most accurate for irrigation control, with only minor misclassifications between ON and OFF states. Ventilation and shading decisions exhibited slightly higher misclassification rates, mainly between “Partial” and “Closed” shading states.

The feature importance analysis revealed that soil moisture and air temperature were the dominant predictors for irrigation, air temperature and CO_2 concentration for ventilation, and light intensity for shading. This ranking is consistent with agronomic knowledge and validates the interpretability of the RF model.

To evaluate the effectiveness of the proposed Random Forest (RF) control algorithm, results were compared against a baseline rule-based control system using the fixed thresholds described earlier (irrigation, ventilation, and shading). Using the same input dataset of 5,000 records, baseline actuator states were generated according to these thresholds, actuator decisions being triggered by fixed threshold values (e.g., irrigation ON if soil moisture < 30% and air temperature > 28 °C; ventilation ON if air temperature > 32 °C or CO_2 concentration > 1000 ppm; shading CLOSED if light intensity > 18,000 lux, PARTIAL if between 10,000–18,000 lux, and OPEN otherwise).

A set of ground truth labels was defined through agronomic expert validation: for each input record, control decisions were reviewed and corrected when necessary to ensure consistency with optimal crop growth requirements. These expert-adjusted labels served as the reference against which both the baseline and the RF predictions were evaluated.

The baseline system achieved its predictions directly by applying thresholds, while the RF model produced predictions after training on 70% of the dataset and testing on 30%. To ensure fairness, the same test subset was used to evaluate both systems.

Performance metrics for the baseline were then calculated as follows:

- Accuracy (%): number of correct actuator state predictions divided by the total number of test samples.
- Precision (%): proportion of true positive predictions for a given control action (e.g., irrigation ON) out of all positive predictions made by the baseline.
- Recall (%): proportion of correctly predicted positive actions out of all ground truth positives.
- F1-score (%): harmonic mean of precision and recall.

For example, if in the test set irrigation ON was required in 500 cases and the baseline system correctly identified 430 of them while producing 50 false positives, the irrigation recall was calculated as 430/500 = 86.0% and precision as 430/(430+50) = 89.6%. Similar calculations were carried out for ventilation and shading.

These values were aggregated across all three controlled parameters to produce average performance metrics. The results showed that the baseline achieved lower scores than the RF model due to its rigid thresholding logic, which did not adapt to overlapping or borderline conditions in the input data.

Figure 2 illustrates the performance comparison between the baseline system and the RF model. The RF algorithm achieved consistently higher values for all metrics—accuracy, precision, recall, and F1-score—demonstrating its superior ability to classify actuator states correctly.

In particular, RF outperformed the baseline by an average of 9–10 percentage points across metrics. It is important to note that the baseline rule-based system was simulated using fixed thresholds, and not implemented as a physical controller. This ensured a fair comparison with the RF model using identical input data.

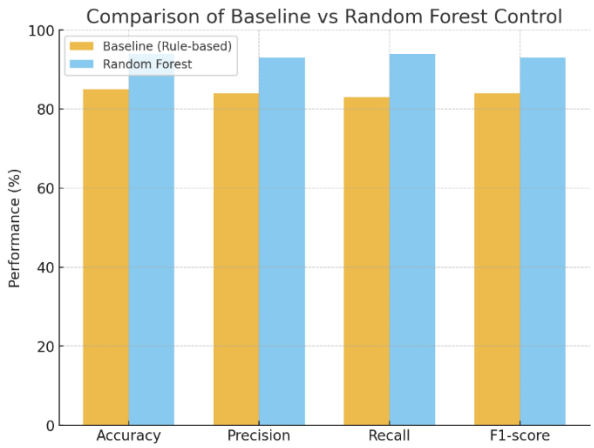

Fig. 2 - Comparison of baseline (rule-based) and Random Forest model performance

Beyond classification performance, the impact of the RF control system on greenhouse microclimate stability was assessed. Figure 3 shows the 24-hour evolution of air temperature and relative humidity under both control approaches. The baseline rule-based control exhibited greater fluctuations in both parameters, while the RF-based system-maintained conditions closer to the optimal range. Specifically, RF reduced the amplitude of temperature oscillations by approximately 40% and humidity oscillations by 35%.

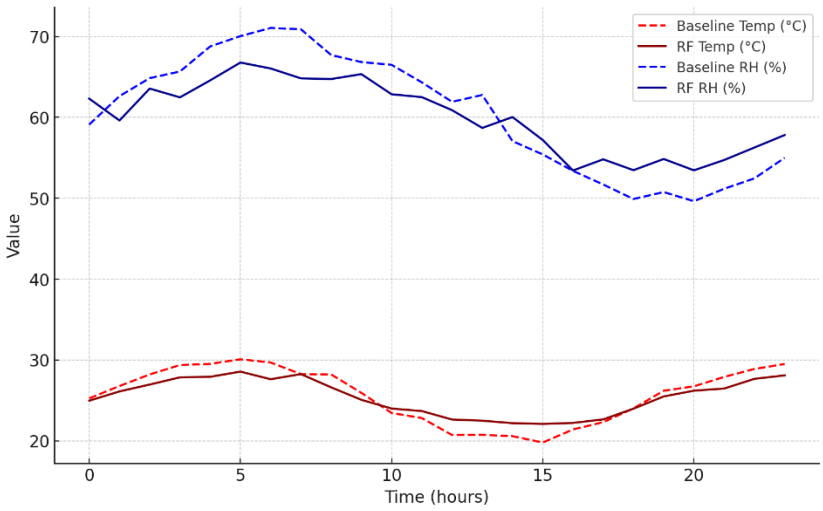

Fig. 3 - Microclimate stability: evolution of air temperature and humidity under baseline (rule-based) and Random Forest control

These results confirm that RF not only improves decision-making accuracy but also contributes to enhanced stability of greenhouse environmental conditions, leading to reduced water and energy consumption and lower plant stress levels.

The following results refer to the simulated deployment of the RF model on a Raspberry Pi 4 gateway integrated into the WSN framework, rather than a physical greenhouse experiment.

The system executed control decisions every 60 seconds, transmitting actuator commands wirelessly to the irrigation valves, fans, and shading screens.

The experimental implementation yielded the following improvements compared to the simulated baseline rule-based control:

- Water consumption reduction: 17% average reduction due to more precise irrigation decisions.
- Energy consumption reduction: 12% reduction in fan usage through adaptive ventilation scheduling.
- Microclimate stability: Variability of air temperature reduced by 15%, and variability of relative humidity reduced by 12%.
- Plant stress indicators**:** Lower incidence of leaf wilting during peak radiation periods, attributed to improved shading control.

Overall, the RF-based control system demonstrated its capacity to enhance resource efficiency while maintaining favorable growing conditions, validating the approach as a viable alternative to traditional rule-based greenhouse control.

DISCUSSION

The results obtained in this study confirm the potential of Random Forest (RF) as an effective tool for greenhouse microclimate control. Compared to the simulated baseline rule-based system, the RF model achieved higher accuracy and stability in decision making. The main reason lies in the ability of RF to capture nonlinear relationships among environmental variables. While rule-based systems rely on fixed thresholds, they fail to adapt to conditions where multiple parameters interact simultaneously. For instance, irrigation demand cannot always be explained solely by soil moisture, as it also depends on air temperature and humidity. The RF model successfully incorporated these interactions, leading to more accurate actuator decisions.

Another key advantage of RF is its robustness to noise and variability in sensor readings. Wireless sensor networks deployed in greenhouses often encounter measurement errors, missing data, or fluctuations due to transient conditions. The bootstrap aggregation (bagging) approach of RF ensures that the model remains stable even under such uncertainty, whereas rule-based systems may generate abrupt or inappropriate control actions.

The feature importance analysis further highlights the interpretability of RF, which is often a limitation of machine learning models. The identification of soil moisture, air temperature, and light intensity as the dominant variables is consistent with agronomic expertise, providing confidence that the model decisions align with practical knowledge. This consistency is essential for building trust among growers and facilitating the adoption of intelligent control systems.

From a practical perspective, the implementation results underline the benefits of RF for resource efficiency. The observed reductions in water and energy consumption, although evaluated against a simulated baseline, indicate that intelligent, data-driven control can significantly improve sustainability in greenhouse operations. These improvements are particularly relevant in the context of climate change, where efficient use of resources has become a major challenge.

Nevertheless, some limitations must be acknowledged. First, the dataset used in this study was generated through simulation based on ranges observed in previous experiments, and therefore real-world variability may be even more complex. Second, the baseline was simulated and not tested in a fully operational rule-based controller. Despite these limitations, the comparative evaluation remains valid as both models were tested on the same dataset under identical conditions.

Overall, the discussion confirms that RF represents a promising alternative to conventional greenhouse control strategies, combining predictive accuracy, robustness, and interpretability. Future work should address the integration of real long-term datasets, predictive models for dynamic weather conditions, and adaptive learning strategies to further improve control efficiency.

While these findings are promising, they are derived from simulated datasets, and real-world testing remains a necessary step to validate performance under uncontrolled environmental variability.

CONCLUSIONS

This study presented the design and simulation of a Random Forest (RF)-based intelligent control algorithm for greenhouse microclimate management. The framework integrated two wireless sensor nodes monitoring soil and air parameters (temperature, humidity, CO_2, and light) with one actuator node controlling irrigation, ventilation, and shading.

The simulation results demonstrated that the RF model outperformed the **simulated baseline rule-based system** across all performance metrics. Specifically, the RF achieved higher accuracy, precision, recall, and F1-score, while also providing interpretable feature importance values that highlighted the dominant role of soil moisture, air temperature, and light intensity in decision making. Comparative analysis showed that the RF reduced misclassifications in actuator states and improved simulated stability of greenhouse microclimate conditions.

The simulation further indicated potential efficiency gains compared to the baseline: water consumption was reduced by approximately 17%, energy use by 12%, while temperature and humidity variability decreased by 15% and 12%, respectively. It must be emphasized that these results were obtained

from a simulation study, not from direct measurements in a real greenhouse, and therefore represent expected rather than measured improvements.

Overall, the findings validate the feasibility of integrating WSN with machine learning algorithms for simulated, adaptive greenhouse control. The proposed approach demonstrates significant advantages over conventional threshold-based methods and establishes a solid foundation for future work.

Future research will focus on extending the framework with real-world greenhouse datasets, testing under different climate scenarios, and integrating predictive models such as LSTM networks and reinforcement learning for adaptive long-term strategies.

ACKNOWLEDGEMENT

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SUSTAINABLE SOUND ABSORBING COMPOSITE STRUCTURES BASED ON ECO-FRIENDLY MATERIALS FOR ROAD NOISE REDUCTION

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STRUCTURI COMPOZITE FONOABSORBANTE SUSTENABILE PE BAZĂ DE MATERIALE ECOLOGICE PENTRU REDUCEREA ZGOMOTULUI RUTIER

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Keywords: *composite materials, road noise reduction, sound-absorbing structures, eco-friendly materials, fir cones, sustainable infrastructure.*

ABSTRACT

The paper presents the development of a prototype of an eco-friendly sound-absorbing panel, intended for use in the vicinity of highways to reduce noise pollution. The composite material is made of fir cones, polyurethane foam, and wool, with the aim of evaluating the potential of these natural and recyclable resources in the construction of alternative sound protection solutions. The experimental samples are subjected to physical characterization tests, targeting essential parameters for durability in the outdoor environment: density, water absorption, thermal conductivity, and acoustic absorption. Considering the specific climatic conditions of road areas, the material is designed to function as a sound-absorbing core in a composite acoustic system. It is proposed to cover it with a perforated sheet of metal, with a mechanical protection role, without significantly compromising the acoustic efficiency. The results aim to integrate this system into the transport infrastructure, contributing to the promotion of eco-friendly materials and the development of sustainable solutions for reducing road and rail traffic noise. To validate the performance, the developed composite materials were benchmarked against a widely used reference material in the field – basalt mineral wool.

REZUMAT

Lucrarea prezintă dezvoltarea unui prototip de panou fonoabsorbant ecologic, destinat utilizării în proximitatea autostrăzilor pentru reducerea poluării acustice. Materialul compozit este realizat din conuri de brad, spumă poliuretanică și lână, cu scopul de a evalua potențialul acestor resurse naturale și reciclabile în construcția unor soluții alternative de protecție fonică. Probele experimentale sunt supuse unor teste de caracterizare fizică, vizând parametri esențiali pentru durabilitatea în mediul exterior: densitatea, absorbția de apă, conductivitatea termică și absorbție acustică. Având în vedere condițiile climatice specifice zonelor rutiere , materialul este conceput să funcționeze ca miez fonoabsorbant într-un sistem acustic compozit. Se propune acoperirea acestuia cu o foaie de tablă perforată, cu rol de protecție mecanică, fără a compromite semnificativ eficiența acustică. Rezultatele urmăresc integrarea acestui sistem în infrastructura de transport, contribuind la promovarea materialelor ecologice si la dezvoltarea unor soluții sustenabile pentru reducerea zgomotului de trafic rutier și feroviar. Pentru validarea performanțelor, materialele compozite dezvoltate au fost comparate cu un material de referință utilizat pe scară largă în domeniu – vata minerală bazaltică.

INTRODUCTION

This paper investigates an innovative composite material, made of shredded fir cones, wool fragmented into small pieces and a synthetic binder, derived from the reuse of textile and vegetable waste. By combining these components, the aim is to obtain a porous structure, capable of efficiently attenuating the propagation of sound waves.

Wool, due to its fibrous structure and natural elasticity, presents favorable sound-absorbing properties, while fir cones contribute to the rigidity and dimensional stability of the composite, while maintaining the ecological character of the solution.

The integration of this composite structure into sound-absorbing panels for highways has the potential to combine high acoustic performance with a reduced environmental impact, by using renewable resources and reusable waste. The study proposes a comparative analysis of the acoustic and mechanical properties of this composite material in relation to basalt mineral wool.

According to a recent study, sound-absorbing panels based on recycled materials prove to be a sustainable and effective solution for reducing noise pollution caused by road traffic, presenting similar performance to conventional materials, such as basalt mineral wool. (*E. A. Singh, N. Dubey, S. Puni (2021). "Eco-Friendly Noise-Absorbing Panels from Waste Materials: A Sustainable Solution to Control Noise Pollution").*

In the same direction, Rubino and collaborators demonstrated that panels obtained exclusively from recycled textile fibers and biopolymers can achieve absorption coefficients of over 0.9 at high frequencies, confirming the potential of renewable materials for acoustic applications. *(Rubino,C., Bonet Aracil,M., Gisbert-Paya, J., Liuzzi,S.,Stefanizii, P., & Martellotta,F.(2019). "Composite Eco-Friendly Sound Absorbing Materials Made of Recycled Textile Waste and Biopolymers. Materials,12(15),2497").*

Nazari and colleagues also highlighted that hybrid panels based on natural fibers and agro-industrial biomass can reduce noise levels by up to 44.9 dB at high frequencies, which shows that ecological and recycled materials can achieve performances comparable to those of conventional solutions. *(Nazari,S., Razavi, M., Alihosseini, F., & Rajak, D.K. (2024) "Effect of Natural Fiber and Biomass on Acoustic Performance of 3D Hybrid Fabric-Reinforced Composite Panels. Polymers, 6(9), 1268).*

MATERIALS AND METHODS

To make the composite materials, natural raw materials and a synthetic binder were used, selected based on the criteria of availability and technological compatibility.

Two variants of composite materials were practically made, with different mass percentages, as follows:

- Recipe 1: 0.7% wool fragmented into small pieces, 70.9% synthetic binder and 28.4% shredded fir cones..

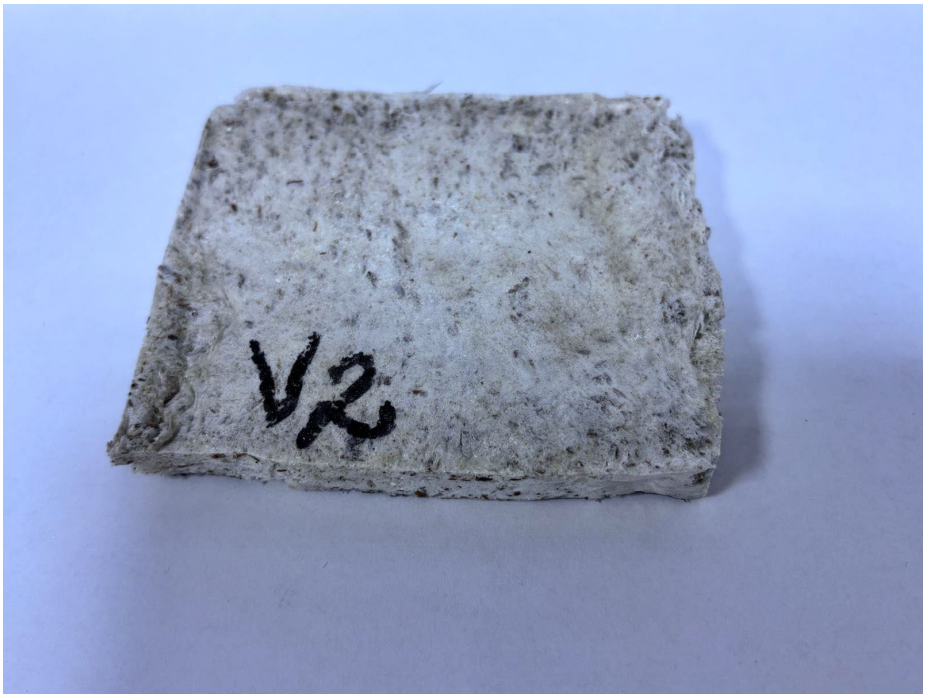

Fig. 1- Appearance of the composite material obtained according to Recipe 1 (noted V2)

Recipe 2: 1.5% wool fragmented into small pieces, 75.8% synthetic binder, and 22.7% shredded fir cones.

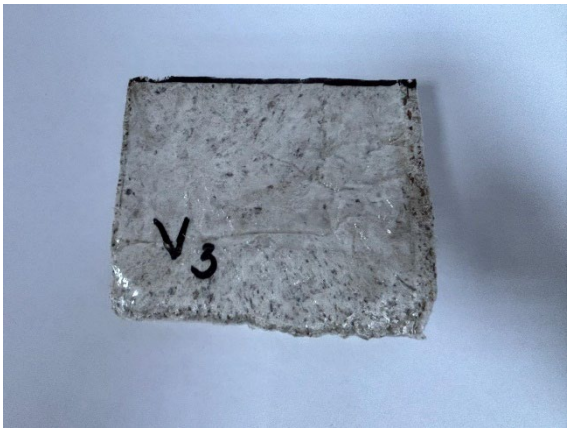

Fig. 2 - Appearance of the composite material obtained according to Recipe 2 (noted V3)

Basalt mineral wool is a versatile and durable material, widely used in thermal insulation panels for buildings and infrastructure, including acoustic panels used on highways, due to its sound-absorbing properties. Its fibrous and porous structure gives it high acoustic absorption, significantly reducing the noise generated by road traffic and contributing to improving the comfort of homes in adjacent areas. *(Agosti,F., Buratti,C., Moretti,E. & Belloni,E. (2015) „Thermal and Acoustic Performance Evaluation of New Basalt Fiber Insulation Panels for Buildings. Energy Procedia, 78, 1211-1216."*

In this study, basalt wool was used as a reference material for evaluating the performance of composite materials made according to recipes 1 and 2. Due to its structure, mineral wool is made up of non-woven and randomly arranged mineral fibers, and the material has a high porosity that provides it with excellent thermal and sound insulation properties, recognized and validated in the construction field.

Fig. 3 - The basalt wool sample obtained as a reference material (noted VM)

For a comparative analysis, samples of the composite materials obtained according to the two recipes (V2 and V3), together with the basalt mineral wool (VM) sample, were subjected to the same experimental tests. The determinations mainly concerned density, thermal conductivity, water absorption and acoustic absorption capacity, parameters relevant for characterizing the performance of sound-absorbing materials.

- **DENSITY MEASUREMENT**

The density of the materials analyzed in this study was evaluated by measuring the dimensions of each specimen with a digital caliper (length, width and height) and by weighing them. Subsequently, the density of the materials was calculated using the following relationship, according to SR EN ISO 29470:2020:

$$\rho = \frac{m}{V} \quad [kg/m^3] \tag{1}$$

where:

m - mass of the specimen expressed in Kg;
V - volume of the specimen expressed in m^3;
This procedure was applied to all experimental samples studied: VM, V2 and V3 to allow comparative evaluation of the proposed solutions.

- **THERMAL CONDUCTIVITY MEASUREMENT**

To determine the thermal conductivity of the materials, the "HESTO-LAMBA-CONTROL A90" equipment from the Icecon Test laboratory in Bucharest was used (Figure 4), which can analyze flat insulating materials, with maximum lengths and widths of up to 300mm and a thickness ranging from 15-90mm. This equipment measures the heat flow through a specimen placed between two plates with different temperatures; the measurement accuracy is ± 3% according to SR EN 12667:2002. The determination of thermal conductivity for all types of analyzed materials was performed using the thermoflux-metric method.

Fig. 4 - Thermal conductivity testing equipment - HESTO-LAMBA-CONTROL A90"

The thermal conductivity coefficient can be calculated by measuring the heat flux through the sample using the following relationship, according to SR EN 12667:2002:

$$\lambda = \frac{\phi * d}{A\,(T_1 - T_2)} \quad [W/mK] \tag{2}$$

where:
ϕ - represents the average power supplied in the measurement area by the heating element;
d - average thickness, in mm;
A - represents the area of the measurement area, in mm^2 ;
T1 - represents the average temperature of the hot face of the specimen [°C];
T2 - represents the average temperature of the face of the specimen [°C].

The thermal resistance R is calculated using the following relationship, according to SR EN 12667:2002:

$$R = \frac{T_1 - T_2}{\phi} A \quad [m^2K/W] \tag{3}$$

where:
ϕ - represents the average power supplied in the measurement area by the heating element;
T1 - represents the average temperature of the hot face of the specimen [°C];
T2 - represents the average temperature of the face of the specimen [°C];
A - represents the area of the measurement area, in mm^2 ;

- **ACOUSTIC ABSORPTION MEASUREMENT**

The experimental determinations of the acoustic absorption variation were carried out using the equipment “Impendance Tube Kit (100Hz – 3200Hz) – Type 4206 A” (Figure 5). This acoustic interferometer is specially designed to cover the frequency range from 100 Hz to 3000 Hz. The determination of the acoustic properties of the studied materials was carried out, in accordance with SR EN ISO 10534-2:2024 and was based on the two-microphone transfer function method, which, based on the normal incidence of sound on the surface of the sample materials, evaluates the acoustic absorption coefficient of the materials.

A sound source (loudspeaker) is mounted at one end of the impedance tube, and a material sample with a diameter of 63.5 mm is placed at the other end. The diffuser generates random, broadband, standing sound waves that propagate as plane waves in the tube, strike the sample, and reflect. The propagation, contact, and reflection result in a standing wave interference pattern due to the superposition of the waves traveling back and forth inside the tube.

Fig. 5 - Acoustic absorption testing equipment - "Impendance Tube Kit (100Hz – 3200Hz) – Type 4206 A"

The normal acoustic reflectance coefficient r can be calculated using the following relationship, according to SR EN ISO 10534-2:2024, as follows:

$$r = \bar{r}e^{j\phi_r} = r_r + jr_i = \frac{H_{12} - H_I}{H_R - H_{12}} e^{2jk_0x_1} \tag{4}$$

where:

r_r - is the real component;

r_i - is the imaginary component;

x_1 - is the distance between the reference plane of the sample and the microphone position;

ϕ_r - is the phase angle of the reflection coefficient at normal incidence;

k_0 - is the complex wavenumber of the waves propagating in air containing the impedance.

The determination of the acoustic absorption coefficient at normal sound incidence can be calculated using the following relationship, according to SR EN ISO 10534-2:2024, as follows:

$$\alpha = 1 - |r|^2 = 1 - \sqrt{r_r^2 + r_i^2}^2 = 1 - r_r^2 - r_i^2 \tag{5}$$

where::

r_r - is the real component;

r_i - is the imaginary component;

- **MEASUREMENT OF WATER ABSORPTION**

The water absorption of the composite material samples (V2, V3) and the basalt mineral wool sample (VM) was determined using the partial immersion method according to SR EN ISO 29767:2019,

ensuring the comparability of the results between materials with different structure and porosity. The samples were conditioned for 6 hours at a temperature of 23°C ±2°C and a controlled relative humidity of 50% RH. Each sample was placed in a container with water so that it was partially immersed for 24 hours. The water level was maintained constant throughout the test.

The water absorption W_p was calculated according to the relationship:

$$Wp = \frac{m_{24} - m_0}{A_p} \quad (6)$$

where:
m_0 - initial mass of the sample, in Kg;
m_{24} - mass of the sample after 24h immersion, in Kg;
A_p - area of the immersed surface, in m^3.

The results were expressed in Kg/m^2 .

EXPERIMENTAL RESULTS

The density of the samples was determined by weighing them and measuring the volume, applying the formula [1]. An electronic scale with an accuracy of 0.01g was used to determine the mass, and the volume was calculated based on dimensional measurements with a digital caliper.

The tests were performed in the laboratory at a temperature of 23±2°C and a relative humidity of 50±5% (Figure 6).

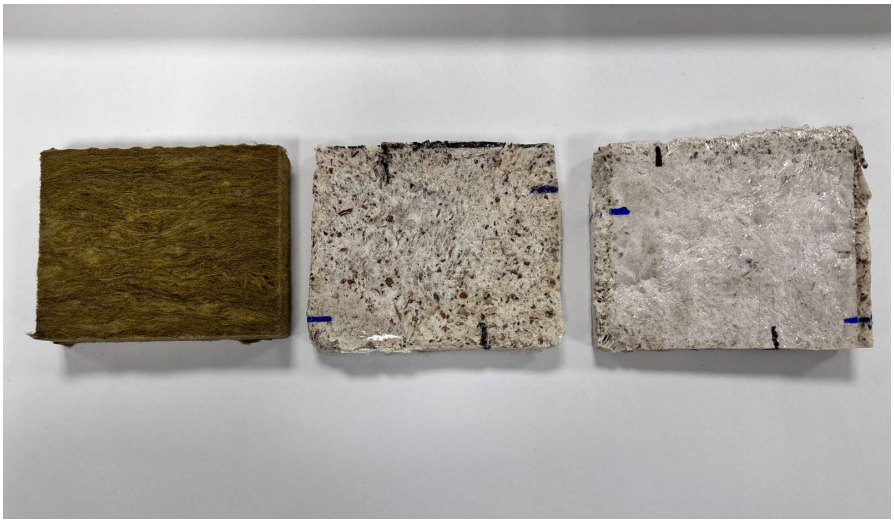

Fig. 6 - Samples prepared for density determination

Following dimensional determinations and weighing of the samples, the density of sample V2 was obtained to be 138.0 kg/m3, the density of sample V3 to be 122.2 kg/m3, and the density of mineral wool to be 100.5 kg/m3, as can be seen in the graph in figure 7.

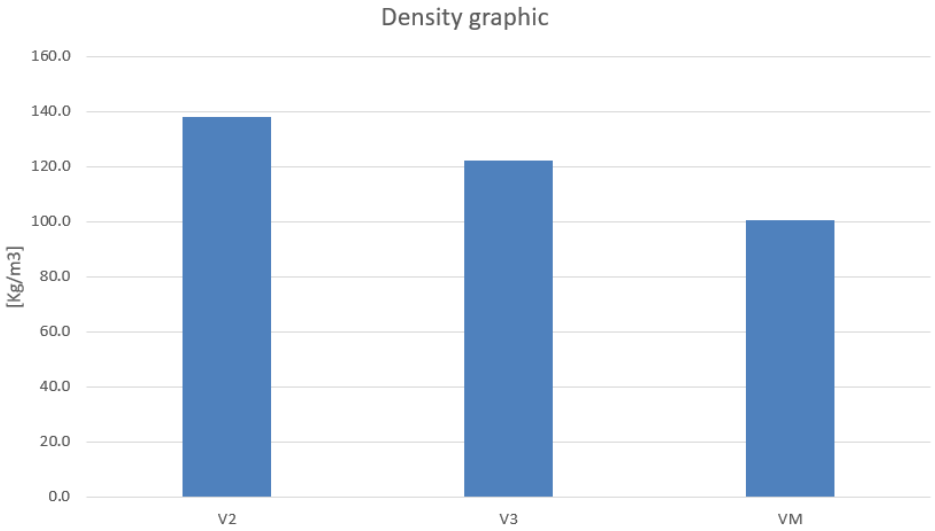

Fig. 7 - Density evaluation of the three materials

In order to evaluate the potential use of the composite material obtained from shredded fir cones, wool fragmented into small pieces and a synthetic binder (V2 and V3), a comparative analysis of **thermal conductivity** with a widely used insulating material – basalt mineral wool (VM) was carried out.

This comparative analysis provides an overview of the thermal performance of the two new recipes and allows highlighting both the advantages and possible limitations.

The following are the **thermal conductivity** values determined for the analyzed materials, obtained from the tests carried out according to the method described above.

Tabel 1

The thermal conductivity values determined for the studied materials are presented in Table 1.

Number of samples	Thermal conductivity coefficient, [W/mK]	Thermal conductivity coefficient, 10°C
V2	0.0450	0.0419
V3	0.0441	0.0410
VM	0.0357	0.0336

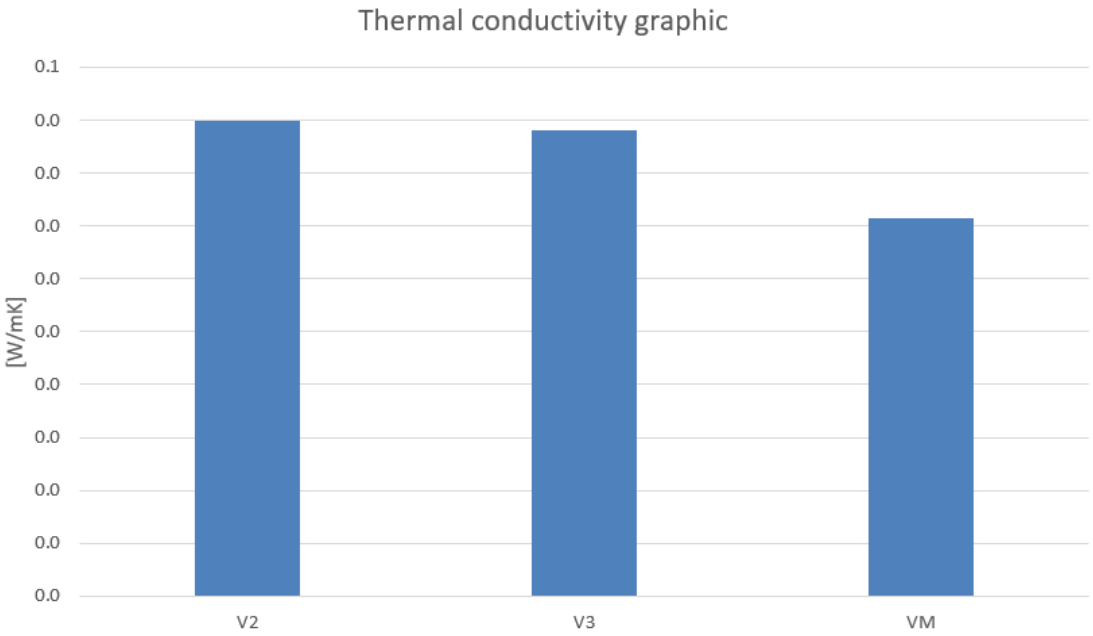

Fig. 8 - Thermal conductivity evaluation of the three types of material

The graph in figure 8 clearly shows the difference between the two composite material recipes (V2 and V3) and the reference material (VM). The values of the thermal conductivity coefficient for V2 and V3 are higher than those of basalt mineral wool, which indicates a lower thermal insulation.

However, it is noted that sample V3 has lower values than V2, confirming a slightly improved thermal performance due to the high proportion of wool. Overall, the graph highlights the positioning of the tested ecological materials between the optimal values offered by basalt mineral wool and the acceptable thresholds for insulating materials usable in construction.

Acoustic absorption coefficient

To determine the acoustic absorption coefficient, the samples were cut into circular shapes with a diameter of 63.5 mm specific to the medium acoustic interferometer, Type 4200 A (Fig.8). The average thickness of the samples is: VM - 20.30 mm, V3 – 14.72 mm and V2 – 13.80 mm

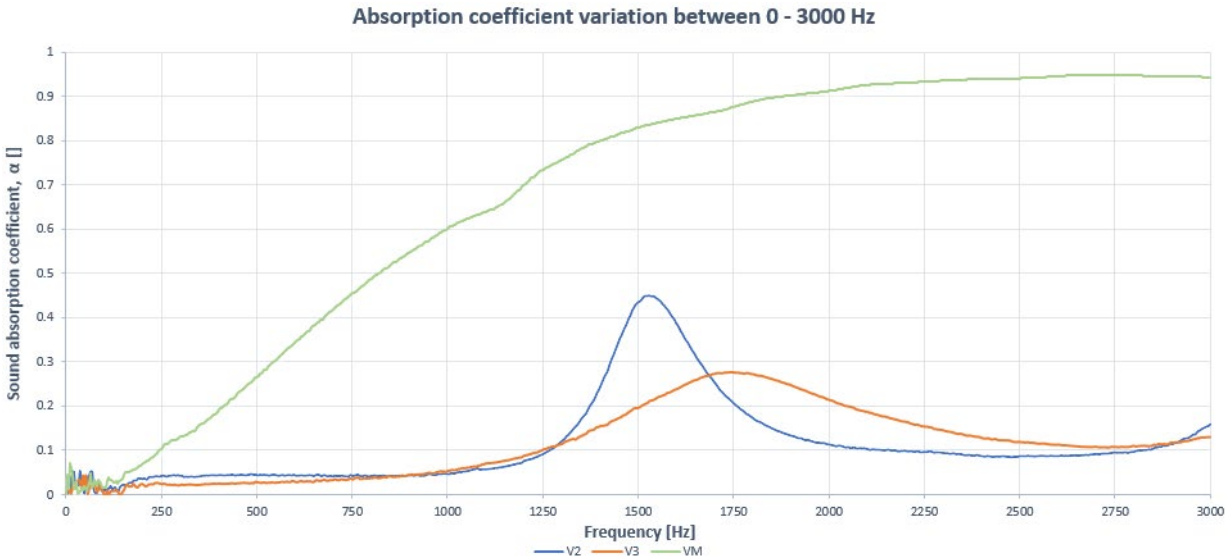

Fig. 9 - Variation of acoustic absorption coefficient, α []

The graph in figure 9 illustrates the variation of the acoustic absorption coefficient for the tested materials (V2, V3 and VM) in the range of 100-3000 Hz. It is observed that basalt mineral wool (VM) shows the best performance over the entire frequency range, reaching values close to 0.9-1.0.

The experimental composite materials (V2 and V3) show lower acoustic absorption, but highlight a differentiated behavior: sample V2 shows a significant peak around the frequency of 1500 Hz (~0.45), while sample V3 has a more uniform, but lower acoustic absorption (~0.25-0.3).

These results suggest that ecological materials can be effective in narrow frequency bands and that optimizing their structure could lead to improved acoustic performances.

Short-term water absorption by partial immersion

The three samples (V2, V3 and VM) were placed together in a clean and airtight container (figure 10). Water was poured into the container to a level of 1 cm, so that the lower part of the samples was in contact with the water.

The samples were left in this position for 24 h to achieve absorption, and were then weighed at predetermined time intervals to determine the increase in mass due to the absorbed water.

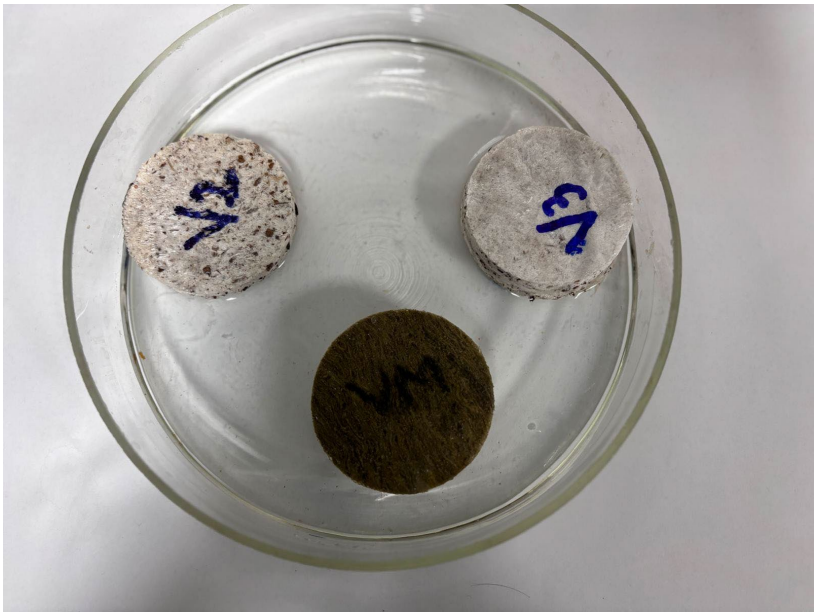

Fig. 10 - Samples V2, V3 and VM on water absorption

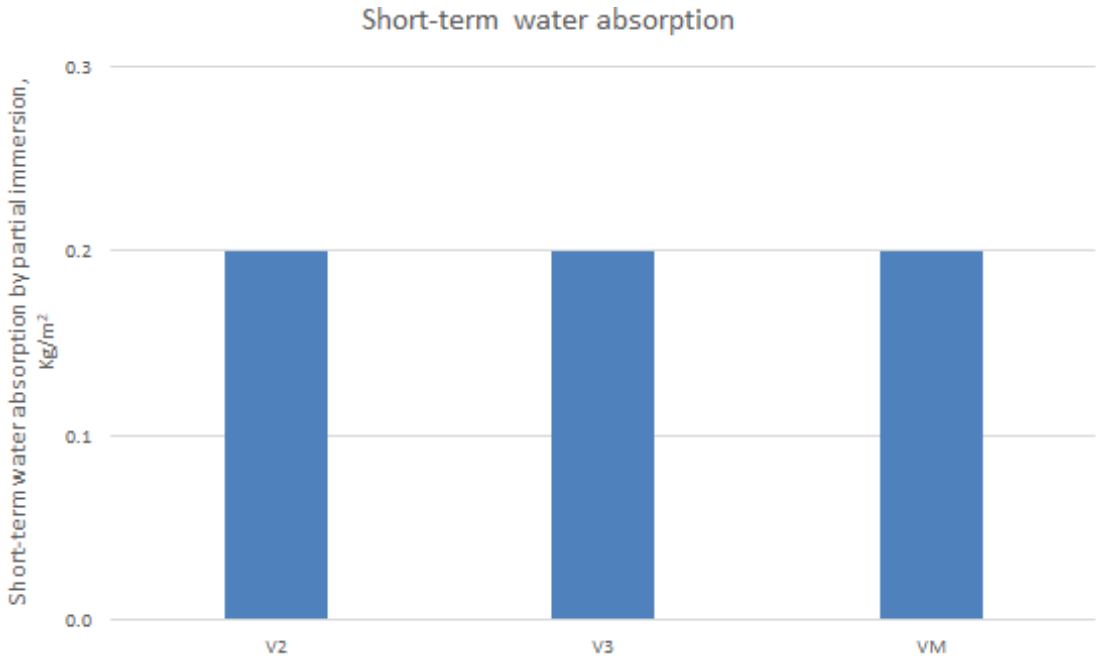

Fig. 11- Water absorption assessment

In the graph in figure 11 it is observed that the three samples presented the same degree of absorption (0.2). This indicates a uniformity of the tested material, which suggests a homogeneous structure and similar physical properties regarding permeability and porosity.

CONCLUSIONS

Based on the tests carried out in this study, the following conclusions are highlighted:

- Basalt mineral wool (VM) presents the best acoustic properties across the entire frequency range, reaching absorption coefficients of 0.9 – 1.0.
- Materials made from crushed fir cones, wool fragmented into small pieces and synthetic binder (V2 and V3) presented higher densities than basalt mineral wool (122-138 Kg/m^3 compared to 100,5 Kg/m^3), but their acoustic efficiency is limited to a narrow frequency band (approximately 1500-1700 Hz).
- The values obtained for thermal conductivity for V2 and V3 (0,041-0,045 W/mK) are comparable, but higher than for basalt mineral wool (0,033 - 0,036 W/mK), which indicates a lower thermal insulation capacity.

- The water absorption of the three analyzed samples (V2, V3 and VM) had the same value, which indicates a uniformity of the materials.
- Even if the acoustic and thermal performances of the experimental materials are inferior to basalt mineral wool, the use of renewable resources and waste highlights a significant potential in the development of ecological solutions, with an impact on the environment.
- The integration of the composite material (V2 or V3) in a panel covered with perforated sheet metal or the combination with other materials could increase both the acoustic performance and the mechanical resistance.

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VALORIZATION OF RENEWABLE RESOURCES FOR THE PRODUCTION OF BIOPLASTICS IN A CIRCULAR ECONOMY

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VALORIFICAREA SURSELOR REGENERABILE PENTRU PRODUCEREA BIOPLASTICELOR ÎNTR-O ECONOMIE CIRCULARĂ

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ABSTRACT

The alarming growth in the production and consumption of conventional plastics, coupled with low recycling rates and their severe environmental impact, has driven increasing interest in sustainable alternatives. Bioplastics, derived either from renewable resources or designed with biodegradability, represent a promising solution to reduce dependence on fossil fuels and to support circular economy strategies. Their classification is based on the origin of raw materials and biodegradation capacity, including polymers such as PLA, PHA, TPS, bio-PE, and PBAT. Recent literature highlights the relevance of mechanical strength, barrier performance, biodegradability, and compostability, which are essential factors for expanding their applications in packaging, agriculture, medicine, textiles, and electronics. Numerous studies also demonstrate the valorization of agro-industrial residues (starch, cellulose, proteins, lignocellulosic materials) for the development of functional bioplastics, confirming both the advantages and the current limitations of these materials. This paper aims to synthesize recent findings on renewable feedstocks used for bioplastic production, the main processing steps, key properties, and application domains, with a particular emphasis on their contribution to the circular economy.

REZUMAT

Creșterea alarmantă a producției și consumului de plastice convenționale, asociată cu rata scăzută de reciclare și impactul negativ asupra mediului, a stimulat interesul pentru dezvoltarea unor alternative sustenabile. Bioplasticele, obținute fie din resurse regenerabile, fie prin procese care le conferă biodegradabilitate, reprezintă o soluție promițătoare pentru reducerea dependenței de combustibili fosili și integrarea în economia circulară. Clasificarea lor se bazează pe originea materiilor prime și pe capacitatea de degradare biologică, fiind incluse materiale precum PLA, PHA, TPS, bio-PE sau PBAT. Literatura recentă evidențiază importanța proprietăților mecanice, de barieră, biodegradabilitate și compostabilitate, factori esențiali pentru extinderea aplicațiilor în ambalaje, agricultură, medicină, textile și electronică. De asemenea, numeroase studii au demonstrat posibilitatea valorificării deșeurilor agroindustriale (amidon, celuloză, proteine, lignocelulozice) pentru obținerea de bioplastice funcționale, confirmând atât avantajele, cât și limitele acestor materiale. Lucrarea urmărește să sintetizeze informațiile recente privind sursele regenerabile utilizate în producerea bioplasticelor, etapele de procesare, proprietățile esențiale și domeniile de aplicare, cu accent pe contribuția lor la o economie circulară.

INTRODUCTION

Conventional plastics, primarily derived from petroleum, have become ubiquitous due to their durability, low cost, and versatility. However, these very properties make them highly problematic for the environment. Their degradation can take hundreds or even thousands of years, during which the resulting fragments, including microplastics and nanoplastics, contaminate water, soil, and food chains, with adverse effects on ecosystems and human health. Moreover, their entire life cycle accounts for approximately 15% of the global carbon budget, contributing significantly to climate change (*Venkatachalam H. and Palaniswamy*

R., 2020; Atiwesh G. et al., 2021; Chilote M.O. and Dhakal H.N.; Mishra S. et al., 2024). Global plastic production exceeds 300 million tons per year, while the recycling rate is only 7%. The remaining share is either incinerated or disposed of in dedicated landfill sites (*Atiwesh G. et al., 2021*). In 2015, approximately 407 million tons were produced, and projections indicate that by 2050 this amount could exceed 1,600 million tons annually if no decisive measures are implemented (*Mishra S. et al., 2024*).

In this context, bioplastics have emerged as a promising alternative. They are polymeric materials that are either biodegradable or produced from renewable biological resources such as corn or potato starch, cellulose, chitosan, or polyhydroxyalkanoates (*Chauhan K. et al., 2024; Pooja N. et al., 2023; Narmatha J. and Amritkumar P., 2021*).

The major difference from conventional plastics lies in the origin of the raw materials and, in many cases, in their ability to decompose more rapidly, thereby reducing the carbon footprint and the dependence on fossil fuels *(Venkatachalam H. and Palaniswamy R., 2020.; Pooja N. et al., 2023*). However, it is important to emphasize that bioplastics are not universally biodegradable. For instance, bio-PE and bio-PP demonstrate degradation resistance comparable to that of their petrochemical analogues, despite being derived from renewable raw materials (*Pooja N. et al., 2023*).

Although research on bioplastics began many years ago, their production has not yet reached a significant industrial scale. In 2019, approximately 1.95 million tons were produced, representing only 0.6% of the global plastic output. According to the data in Figure 1, the evolution of these volumes in recent years can be observed, as well as the anticipated growth trends for the coming period (*Costa A. et al., 2023*).

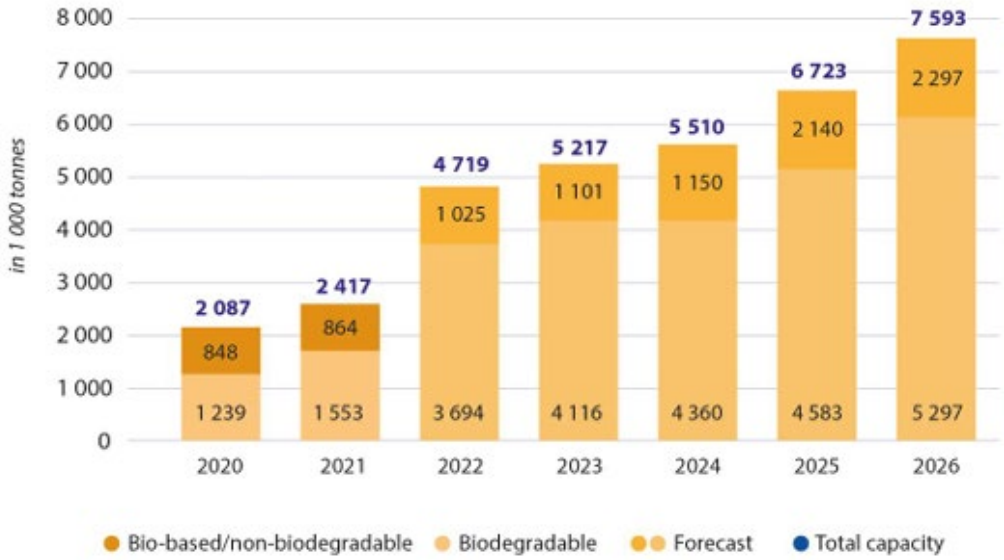

Fig. 1 - Estimates of global bioplastics production for the period 2021–2026
(*Costa A. et al., 2023*)

Figure 1 illustrates the projected evolution of global bioplastics production capacities between 2020 and 2026, including both biodegradable types and those derived from biological resources that do not naturally decompose. In 2020, total production was approximately 2.1 million tons, and by 2026 it is expected to reach around 7.6 million tons. Both categories will expand, although biodegradable bioplastics are projected to grow at a faster rate. Nevertheless, bio-based but non-biodegradable plastics will remain dominant. The most significant increase is anticipated during the period 2024–2026.

MATERIALS AND METHODS

The diversity of existing bioplastics arises both from the variety of raw materials used and from the processes by which they are transformed. To better understand their characteristics and potential applications, bioplastics can be classified according to several criteria, the most common being the origin of the resources and their biodegradability, as well as the chemical composition of the base material.

Bioplastics can first be classified according to the source of the raw material and their biodegradability:

- Bio-based and biodegradable: obtained from renewable resources and capable of decomposing under specific conditions. Examples include polylactic acid (PLA),

polyhydroxyalkanoates (PHA), and thermoplastic starch (TPS) *(Costa A. et al., 2023; Ahsan W.A. et al., 2023).*

- Bio-based and non-biodegradable: produced from renewable raw materials but exhibiting resistance to degradation similar to that of conventional plastics. Examples include bio-based polyethylene (bio-PE), bio-based polyethylene terephthalate (bio-PET), and bio-based polyamides (bio-PA) *(Costa A. et al., 2023; Ahsan W.A. et al., 2023).*
- Fossil-based and biodegradable: derived from fossil resources but with properties that allow biological decomposition. Examples include polybutylene adipate-co-terephthalate (PBAT), polycaprolactone (PCL), and polybutylene succinate (PBS) *(Ahsan W.A. et al., 2023).*

From the perspective of composition, bioplastics can be derived from a wide range of natural raw materials:

- Starch-based: produced from cereals or tubers (corn, potatoes, wheat), usually combined with other biodegradable polymers such as PLA, PBS, PBAT, PCL, or PHA.
- Cellulose-based: derived from wood, plant fibers, or bamboo, in the form of esters such as acetate, nitrate, butyrate, or propionate.
- Protein-based: produced from gluten, casein, albumin, whey, or soy protein *(Dalmia J. and Wadiye G., 2020)*.
- Aliphatic polyesters: obtained through bacterial fermentation of low-cost carbon sources, including PHA, PHB, PLA, PGA, and PCL.
- Bio-based polyamides: formed through the reaction between diamines and dicarboxylic acids, for example from ricinoleic acid or sebacic acid.
- Bio-based polyethylene: derived from ethylene obtained through the fermentation of ethanol sourced from sugarcane or corn.
- Lipid-based polymers: obtained from vegetable or animal triglycerides, such as sunflower oil, soybean oil, or castor oil *(Dalmia J. and Wadiye G., 2020).*

At the global level, agricultural activities and related industries (such as food processing, alcohol production, forestry, and sugar manufacturing) generate very large amounts of plant residues, estimated at nearly 933 million tons annually. Although these wastes can be used as fertilizers, in paper production, or as sources of biofuels, most are incinerated or landfilled, with negative environmental impacts.

Their integration into the circular economy through conversion into bioplastics offers valuable opportunities, particularly due to their high content of polysaccharides such as starch, cellulose, chitin, and pectin. Figure 2 briefly illustrates the transformation stages of these resources, from extraction and processing to applications and end-of-life management, a process influenced by the type of biomass and its chemical composition (*Negrete-Bolagay D. and Guerrero V.H., 2024*).

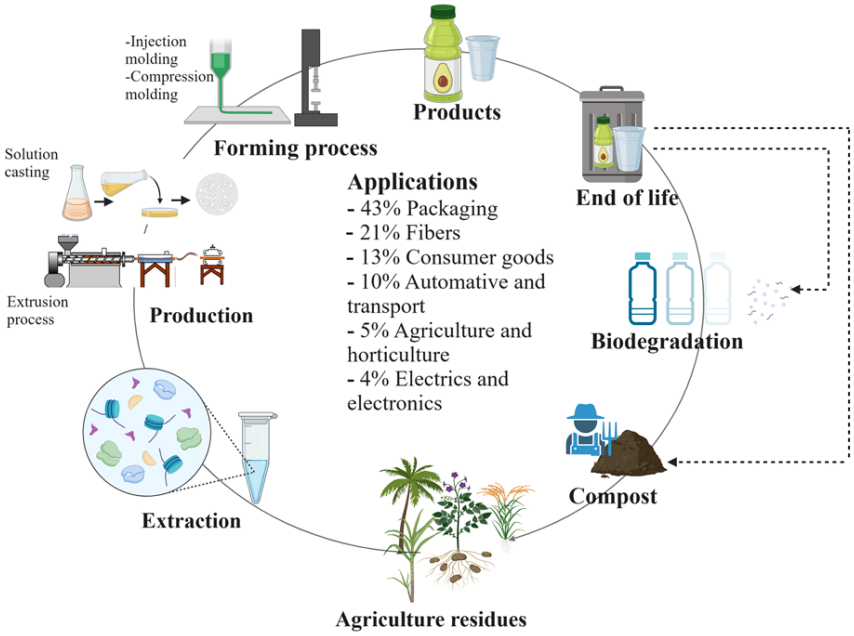

Fig. 2 - Bioplastic production and applications derived from agricultural residues
(*Negrete-Bolagay D. and Guerrero V.H., 2024*)

The performance of bioplastics is closely linked to their physical properties and behavior in the environment. Among the most important are mechanical properties, which determine strength and durability, barrier properties, which are essential for applications such as food packaging, as well as biodegradability and compostability, which define how they are integrated at the end of their life cycle within the circular economy.

Table 1 summarizes these characteristics based on recent studies.

Table 1

Properties of bioplastics

Mechanical properties	Barrier properties	Biodegrability	Compostability	References
Tensile strength, Young's modulus, elongation at break	Oxygen, CO_2, water vapor permeability; UV protection	Discussed for PLA, PHA, TPS	Addressed in relation to food packaging standards	(*Somoghi R. et al., 2025*)
Effect of plasticizers on strength and flexibility	Barrier to oxygen and moisture	Tested under different environmental conditions	Mentioned for PLA, PHA and blends	(*Shi X. et al., 2025*)
Tensile strength, elongation, structural changes during composting	-	Monitored via mass loss and property degradation	Long-term composting studies (90–365 days)	(*Myalenko D. and Fedotova O., 2023*)
Comparative analysis of mechanical reinforcement strategies	Permeability and stability considerations	Degradation in soil and water	Theoretical discussion of compostability	(*Attallah O.A. et al., 2021*)
-	-	Tested in soil, freshwater, marine, and industrial environments	Compared between industrial composting and natural settings	(*Gadaleta G. et al., 2025*)

Due to their structural and functional diversity, bioplastics can be applied across a wide range of fields, from packaging and agriculture to medicine and emerging industries such as textiles and electronics. Each sector leverages specific properties of these materials, such as mechanical strength, barrier performance, or biodegradability.

Table 2 summarizes the main application areas and representative examples reported in the scientific literature.

Table 2

Examples of bioplastic applications in packaging, agriculture, medicine, and electronics

Packaging	Agriculture	Medicine and Biotechnology	Textiles and Electronics
PLA and PHA films, active/smart packaging, food trays, disposable films, bioplastic food packaging materials (*Shi X. et al., 2025 ; Ibrahim N.I. et al., 2021; Elkaliny N.E. et al., 2024*)	PLA and PHA films, active/smart packaging, food trays, disposable films, bioplastic food packaging materials (*Ibrahim N.I. et al., 2021*; *Negrete-Bolagay D. and Guerrero V.H., 2024)*	Drug delivery coatings, wound dressings, sutures, scaffolds for tissue engineering, biomedical implants and prosthetics (*Ibrahim N.I. et al., 2021*; *Negrete-Bolagay D. and Guerrero V.H., 2024.*; *Elkaliny N.E. et al., 2024.*)	Biopolymer fibres for clothing, electronics casings, biodegradable electronic components, textile additives, biopolymer composites (*Ibrahim N.I. et al., 2021*; *Negrete-Bolagay D. and Guerrero V.H., 2024.*; *Elkaliny N.E. et al., 2024.*)

In addition to classifications and functional properties, bioplastics exhibit both significant advantages and limitations that influence their large-scale adoption. The main benefits include the use of renewable resources, integration into the circular economy, and the potential to reduce plastic pollution. At the same time, high production costs, sometimes lower performance compared to conventional materials, and the requirement for specific conditions for biodegradation remain major challenges.

Figure 3 illustrates these aspects in a comparative manner (*Gadaleta G. et al., 2025; Pires J.R.A. et al., 2022; Di Bartolo A. et al., 2021 ; Nicolau A.-M. and Petcu P., 2025; Jha S. ET AL., 2024 ; Abe M.M. et al., 2021; Stasiškiene Ž.; B. et al., 2022 ; Bartolucci L. et al., 2023*).

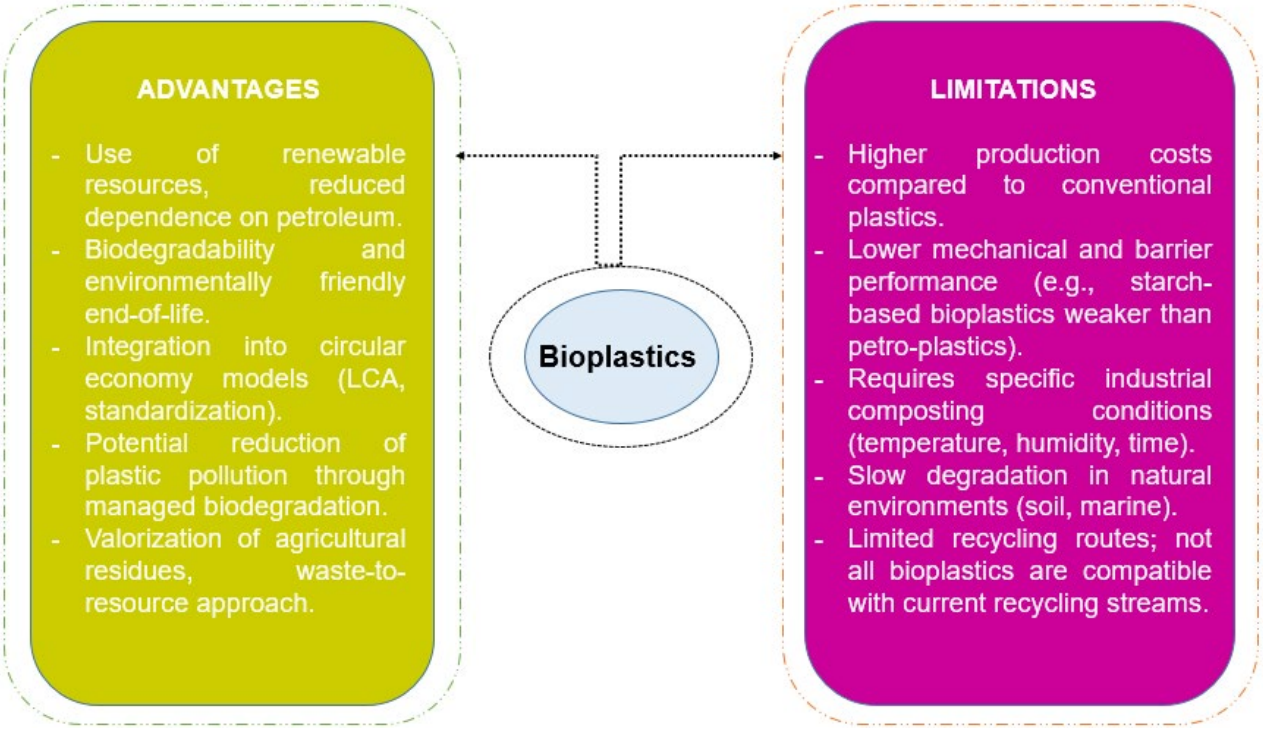

Fig. 3 - Comparative summary of the advantages and limitations of bioplastics

RESULTS

The scientific literature provides multiple examples demonstrating that plant residues and by-products can be converted into bioplastics with functional and environmentally friendly properties. The following section presents several recent studies that are relevant to the application of circular economy principles.

The study (*Torche A. et al., 2025*) utilized cassava starch in combination with onion peel powder, an agro-industrial by-product often discarded as waste, to develop bioplastics intended for food packaging. By

optimizing the composition through statistical methods, films were obtained with tensile strength values of up to 3.87 MPa and a biodegradability rate of approximately 30% after 30 days.

Recent research (*Alves L.T.d.O et al., 2024*) focused on producing biofilms based on proteins extracted from sunflower seeds, a renewable and abundant resource often obtained as a by-product of the vegetable oil industry. To enhance the material's properties, these proteins were combined with locust bean gum, a natural polysaccharide used as a thickening and stabilizing agent.

Analyses showed that higher proportions of gum led to more uniform film structures, increased mechanical strength, and improved barrier performance against water vapor and oxygen, which are essential features for food packaging. At the same time, solubility and biodegradability tests confirmed that these films maintained their eco-friendly profile, degrading rapidly under natural conditions.

Another recent study (*Santos J.F. et al., 2025*) investigated the improvement of cassava starch-based bioplastics by incorporating an alcoholic extract from the Amazonian plant *Vismia guianensis*, which is rich in polyphenolic compounds with antioxidant and antimicrobial effects. Films obtained by the casting method, with extract concentrations ranging from 0.2% to 1.0%, were characterized using physicochemical and mechanical techniques.

The results showed that the extract interacts with starch chains through hydrogen bonding, leading to improved flexibility, thermal stability, and mechanical strength, particularly at the 0.2% concentration. In addition, the films acquired extra functional properties, such as antioxidant and antimicrobial activity, making them promising not only for sustainable packaging but also for biomedical applications.

Waisarikit, A. et al. (*Waisarikit A. et al., 2025*) explored the use of spent coffee grounds from the coffee industry as a natural additive to enhance polylactic acid (PLA), a biopolymer employed in the production of biodegradable horticultural bags. By extracting residual oils from the coffee grounds, stable particles (exSCG) were obtained and incorporated at concentrations of 5–15% into the PLA matrix, followed by processing through extrusion and film blowing. The results showed that the addition of exSCG increased material flexibility, reduced UV light transmission, and accelerated soil biodegradability, while maintaining mechanical properties suitable for practical use. The optimal composition was identified at 10% exSCG, providing a balance between processability, mechanical performance, and controlled degradation.

Another material that can be valorized is corn husk (*Motshabi N. et al.,2025*), which represents an important source of cellulose nanofibrils. These can enhance the mechanical strength, thermal stability, and barrier properties of bioplastics while preserving their biodegradability. Similarly, sugarcane bagasse (*Hassan S. et al., 2024*), an abundant lignocellulosic residue, can be converted through microbial processes into polyhydroxyalkanoates (PHA). These bioplastics are fully biodegradable and provide a sustainable alternative to conventional plastics.

The study (*Ugozor A.O. et al., 2025*) demonstrated the potential for producing biodegradable bioplastics from agricultural residues such as bean husks, plantain peels, and cork stoppers from wood. Cellulose was extracted from these materials through acid-alkaline treatments and subsequently converted into cellulose acetate via acetylation reactions. Yields varied depending on the source used, with the highest recorded for bean husks (45.5% cellulose and 80% cellulose acetate).

Tests confirmed significant biodegradability within approximately four weeks, highlighting the potential of these waste streams to serve as raw materials for sustainable bioplastics.

CONCLUSIONS

Bioplastics are emerging as a sustainable alternative to conventional plastics, playing a key role in reducing dependence on fossil resources and limiting pollution caused by traditional plastic.

The use of renewable resources and agro-industrial residues, such as starch, cellulose, proteins, and lignocellulosic materials, demonstrates the potential of these streams to be transformed into value-added raw materials, directly contributing to the development of the circular economy.

Mechanical and barrier properties, together with biodegradability and compostability, are decisive factors for the large-scale adoption of bioplastics, particularly in sectors such as packaging, agriculture, medicine, textiles, and electronics. However, current limitations, including high production costs, sometimes lower performance compared to conventional materials, and the need for specific conditions for biodegradation, require intensified research and process optimization.

The integration of bioplastics into global economic chains can be accelerated through innovation, standardization, and supportive public policies, paving the way for a genuine transition to a circular economy.

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CURRENT STATE OF RESEARCH ON THE INFLUENCE OF VIBRATIONS ON THE HUMAN BODY OF VEHICLE OPERATORS

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STADIUL ACTUAL AL CERCETĂRILOR PRIVIND INFLUENȚA VIBRAȚIILOR ASUPRA ORGANISMULUI UMAN AL CONDUCĂTORULUI AUTO

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ABSTRACT

Exposure to mechanical vibrations represents a major occupational health and safety risk, particularly in sectors that involve prolonged operation of road vehicles or heavy machinery. This review article provides a comprehensive and critical analysis of the current scientific literature concerning the influence of vibrations on the human body, with a specific focus on Whole-Body Vibration (WBV) exposure. It defines the fundamental concepts related to vibration, including physical characteristics (frequency, amplitude, and direction), predominant sources of vibration within the vehicle–driver system, and the pathways through which these vibrations are transmitted to the human body. This paper explores biomechanical and physiological correlations between vibration parameters and human anatomical structures, highlighting both acute and chronic health effects such as musculoskeletal disorders, intervertebral disc degeneration, accelerated fatigue, and decreased cognitive performance. It also reviews international exposure assessment criteria in accordance with ISO 2631-1 standards and current occupational health regulations. Ultimately the current state of research in the field of whole-body vibration (WBV) is synthesized, highlighting emerging investigative directions, existing knowledge gaps, and the pressing need to develop advanced methods for monitoring and mitigating vibrations transmitted to the human body in the context of increasingly technologized mobility. In this regard, modern systems for the acquisition and processing of experimental vibration data affecting the human body—specifically the vehicle operator—are presented and analysed, aiming to substantiate practical solutions for reducing the risks associated with occupational exposure.

REZUMAT

Expunerea conducătorilor auto la vibrații mecanice reprezintă un factor de risc major pentru sănătatea și siguranța ocupațională, în special în sectoarele care implică operarea prelungită a vehiculelor rutiere sau utilajelor grele. Acest articol de tip review oferă o analiză comprehensivă și critică a literaturii de specialitate privind influența vibrațiilor asupra organismului uman, cu accent pe expunerea de tip Whole-Body Vibration (WBV). Sunt definite conceptele fundamentale legate de vibrații, incluzând caracteristicile fizice (frecvență, amplitudine, direcție), sursele predominante ale vibrațiilor în sistemul vehicul–șofer și modalitățile de transmitere a acestora către corpul uman. Lucrarea abordează corelațiile biomecanice și fiziologice dintre parametrii vibrațional și structura anatomică a organismului uman, evidențiind efectele acute și cronice ale expunerii, precum: tulburări musculo-scheletale, afectarea discurilor intervertebrale, oboseală accelerată și diminuarea performanței cognitive. De asemenea, sunt analizate criteriile internaționale de evaluare a expunerii la WBV, în conformitate cu standardele ISO 2631-1 și reglementările în vigoare privind sănătatea ocupațională. În final, este realizată o sinteză a stadiului actual al cercetărilor în domeniul WBV, punând în evidență direcțiile emergente de investigare, lacunele de cunoaștere existente și necesitatea dezvoltării unor metode avansate de monitorizare și atenuare a vibrațiilor transmise întregului corp în contextul unei mobilități din ce în ce mai tehnologizate. În acest sens, sunt prezentate și analizate sisteme moderne de achiziție și prelucrare a datelor experimentale privind vibrațiile la care este supus organismul uman – conducătorul auto, în scopul fundamentării unor soluții practice de reducere a riscurilor asociate expunerii ocupaționale.

INTRODUCTION

The present review article aims to provide a comprehensive and well-documented analysis of the scientific literature concerning the influence of vehicle-induced vibrations on the human body of the driver, with the purpose of positioning this research topic within the current context of the field. In order to achieve the proposed objectives, several essential directions of investigation are addressed, structured as follows: the definition of vibrations and identification of their generation sources within driver–vehicle systems; the analysis of physiological and biomechanical effects of vibrations on the human body; the assessment of exposure levels to Whole-Body Vibrations (WBV) according to current international standards; the examination of relevant anatomical characteristics influencing vibration transmission; and the synthesis of the current state of research regarding WBV and its implications on occupational health.

This approach aims to establish a scientific foundation for understanding the relationship between vibration parameters and the human biological structure in the context of vehicle operation under mechanically demanding environments.

Vibrations experienced by drivers represent a ubiquitous phenomenon resulting from the complex interaction between vehicle systems and road surface irregularities. These vibrations affect a wide range of operators — from commercial vehicle drivers and agricultural machinery operators to heavy equipment operators — exposing them to mechanical stressors that may, over time, lead to musculoskeletal disorders and neurological impairments. Vibrations are defined as mechanical oscillations of a body around its equilibrium position, characterized by specific parameters such as frequency, amplitude, and direction, which are influenced by both internal and external dynamic factors *(Blanks, A. M., et al. 2022; Shen, C.-L., et al. 2022; Zhou, Y., et al. 2022; Mester, J., et al. 2021; Ramoneda-Rabat, M., et al. 2024)*.

In the context of motor vehicles, the main sources of vibration include the engine, transmission, suspension system, road surface irregularities, and the interaction between the tires and the contact surface. The transmission of vibrations to the human body occurs through contact points such as the seat, steering wheel, and floor, while the biomechanical response depends on both the vibration parameters and the posture adopted during driving. Under Whole-Body Vibration (WBV) conditions, the body movements occur in a synchronous manner, manifesting as a global dynamic response of the human mass relative to the excitation source *(Mirakhorlo, M. et al. 2022; Desai, R. et al. 2024; Desai, R. et al. 2023; Cvetković, M. et al. 2023; Happee, R. et al. 2023)*.

The analysis of whole-body transmitted vibrations focuses on the critical frequency range of [0–80] Hz, as specified by ISO 2631, considering their significant impact on the physiological functions of exposed operators (ISO 2631-1, 1997). In the case of Whole-Body Vibrations (WBV), various anatomical regions of the human body come into direct contact with the vibration source — a representative example being the operating environment of agricultural vehicles such as tractors — where the transfer of mechanical energy disturbs physiological homeostasis, induces discomfort, and affects long-term health. Prolonged exposure may lead to musculoskeletal disorders, particularly affecting the spinal column and joint structures.

The assessment of vibration severity is based on three fundamental criteria: reduction of comfort, interference with task performance, and deterioration of health status. The health effects are influenced by three primary factors: the threshold value of exposure without adverse effects, the dose–response relationship between vibration magnitude and the severity of outcomes, and the latency period between the initial exposure and the onset of symptoms. High-risk exposure environments include off-road vehicles (tractors, agricultural machinery) and heavy road vehicles (trucks, buses), in which vibrations are recognized sources of discomfort and potential occupational injuries *(Singh, R. et al. 2022; Barač, G. et al. 2025; Melo, R. 2019)*. The vibrational behavior of the vehicle, perceived as driving dynamics, manifests predominantly within the frequency range below 20 Hz, with acceleration amplitudes sufficiently high to be transmitted and perceived by the driver. Vibrations generated by the vehicle structure — particularly those associated with pitch, roll, and yaw motions — are directly correlated with the dynamic characteristics of the suspension system, chassis, and body, representing key components of the vehicle–terrain interaction. These vibrations are transmitted through the wheels as a result of contact with surface irregularities and subsequently propagate through the vehicle structure toward the driver's contact points *(Vlădut, N., V., et al. 2024; Burdzik, R. 2023; Dumitriu, M. et al. 2023; Zhang, Y. et al. 2021; Zhou, Y. 2023)*.

For the purpose of contextualizing the analyzed experimental data, it is necessary to provide a technical characterization of the vehicle employed in the studies concerning the influence of vibrations on the human body.

The vehicle of interest is the agricultural tractor — a self-propelled machine, equipped with either wheels or tracks, designed to provide traction and power for mounted, semi-mounted, or towed implements. The construction characteristics, total mass, axle load distribution, suspension stiffness, seat geometry, and cabin configuration are determining factors of the overall vibrational behavior of the system, directly influencing both the level and nature of the operator's exposure to Whole-Body Vibrations (WBV) *(Guruguntla, V. et al.2023; Mei, Y. et al. 2023; Barrie, A. et al 2024)*.

Self-propelled agricultural vehicles of the tractor type can be classified according to the type of engine with which they are equipped, as follows: thermal engine tractors and electric engine tractors, as illustrated in Figure 1.

a) **b)**

Fig. 1 - Self-propelled agricultural vehicle of the tractor type: (a) equipped with a thermal engine; (b) equipped with an electric engine

Studies conducted by various authors (*Mitroi, M. F., 2020; Deulgaonkar, V. R., 2012; Harikrishnan, P., 2017; Hiemstravan, M., 2014*) highlight that vibrations and shocks transmitted through the vehicle structure — particularly via the floor, seat, and other cabin components — are directly perceived by the driver, influencing both biomechanical comfort and physiological exposure. The specialized literature examines the behavior of the tire–wheel system, schematically illustrated in Figure 2, emphasizing the transmission path of random vibrations from the tire–ground contact to the suspension system (*Mitroi, M., 2016*).

Vibrations are partially attenuated by the elastic elements of the tire and suspension before being retransmitted through the vehicle's supporting structure and, ultimately, to the seat. Irregularities in the driving surface induce initial shocks at the wheels, which are subsequently transformed into lower-frequency oscillations that have a direct impact on the perception of comfort and driving safety.

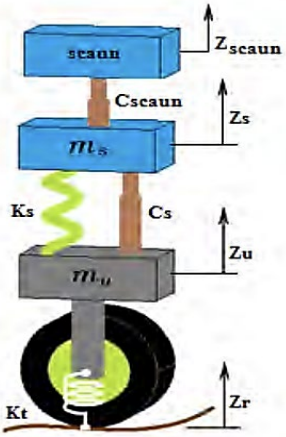

Fig. 2 - Transmission of random vibrations through the tire–wheel system

MATERIALS AND METHODS

This chapter provides a systematic overview of the essential aspects related to the assessment of vibration impact on driver health, with a focus on describing the human body's resonance frequencies in functional positions (standing and seated), determining the exposure levels to Whole-Body Vibrations (WBV), and presenting the methods and equipment employed for experimental data acquisition and processing.

Current methodologies for quantifying accelerations transmitted to the human body are described, along with the measurement systems used to capture vibrational signals at critical contact points (seat, floor,

backrest), in accordance with the applicable international standard (ISO 2631-1). This integrated approach enables an accurate characterization of biomechanical exposure and facilitates the evaluation of health risks to drivers as a function of the measured dynamic parameters.

From a physical and anatomical perspective, the human body represents a highly complex system subjected to shocks and vibrations, which, under certain conditions, may adversely affect health status. When seated, the human body is exposed to vibrations generated by the type of vehicle used during operation on different terrain surfaces and at varying driving speeds. The factors influencing the impact of vibrations on the human body include vibration amplitude, the distance between the subject and the vibration source, body posture, mode and duration of exposure, frequency range, and the direction of vibration propagation. Mechanical influences become significant when vibration amplitudes exceed specific critical thresholds, leading to potential damage to internal organs. In cases where excitation of the nervous system induces a biological response, the consequences may include reduced concentration capacity during driving, the onset of fatigue, and diminished attention levels. Table 1 presents the main resonance frequencies of the human body in standing and seated positions *(Griffin, M., J.2006)*.

Table 1

Resonance frequencies of the human body in standing and seated positions

Position	Frequency [Hz]	Results
Standing	1 Hz	The displacement amplitudes of the pelvis, shoulders, and head range between 20% and 30% of the amplitude of the vibrating surface movements and progressively decrease with increasing vibration frequency
	2-3 Hz	It can be observed that relative maxima occur in the oscillation amplitudes at the shoulder and head levels, indicating localized resonance effects
	Peste 5 Hz	The head movement occurs predominantly along the vertical axis, with an amplitude corresponding to approximately 10–30% of the horizontal movement amplitude of the vibrating surface
Seated	1,5 Hz	The results indicate a significant amplification of oscillations in the hip and pelvic regions, suggesting localized resonance effects
	3 Hz	The results reveal a considerable increase in oscillation amplification at the head level, indicating a higher susceptibility to vertical resonance effects
	1-3 Hz	At specific critical resonance frequencies, the system exhibits a significant amplification of its dynamic response to vibrations
	Peste 5 Hz	Head motion is predominantly manifested along the vertical axis, with an amplitude accounting for approximately 10–30% of the horizontal vibration amplitude of the surface

The specialized literature summarizes the health effects caused by whole-body vibration exposure, particularly at resonance frequencies. These effects are presented in Table 2, highlighting the direct relationship between resonance frequencies and the various associated physiological disorders *(Rasmussen, G., 1996)*.

Table 2

Health effects associated with whole-body vibration exposure

Frequency [Hz]	Adverse health effects
4-9	General discomfort sensation
13-20	Head-related symptoms
6-8	Mandibular symptoms
13-20	Impact on speech
12-16	Sensation of a lump in the throat
5-7	Chest pain
4-10	Abdominal pain
10-18	Urge to urinate
13-20	Increased muscle tone
4-8	Impact on respiratory movements
4-9	Muscle contractions

The phenomenon of resonance occurs when the frequency of vibrations generated by the tractor coincides with the natural frequency of certain tissues or organs of the operator. In such situations, even vibrations with relatively small amplitudes can cause significant displacements of internal organs, which may

lead to pronounced discomfort and the development of serious health disorders *(Gao, R. et al. 2021; Peretti, A. et al. 2023)*.

To comprehensively evaluate the effects of vibrations on the human body, it is essential to measure acceleration along well-defined axes and to correlate these measurements with the analysis of vibration frequencies, amplitudes, and exposure duration.

Acceleration is assessed along three principal axes corresponding to the directions of motion and the orientation of the human body: longitudinal axis (Z): extending from the feet or pelvis to the head, responsible for evaluating vertically transmitted vibrations, which have the greatest impact on the spinal column and torso; transverse left–right axis (X): measures lateral accelerations that affect the operator's balance and lateral stability; transverse front–back axis (Y): measures vibrations in the antero–posterior direction, influencing stability and forward–backward body movements. These directions are perpendicular to the three principal planes of the human body, as illustrated in Figure 3, providing a comprehensive view of how vibrations propagate through the body.

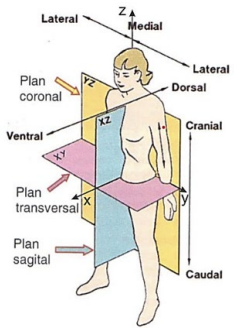

Fig. 3 - Principal planes of the human body and measurement axes according to ISO 2631-1

An essential method for measuring whole-body transmitted vibrations is based on compliance with the guidelines provided by the most widely used standards in this field. These standards offer precise instructions for the accurate assessment of vibration exposure and are summarized in Table 3.

Table 3

Main international standards for the assessment of whole-body vibration exposure

Applicable international standards	Description
ISO 2631-1(2001)	Mechanical vibration and shock — Evaluation of human exposure to whole-body vibration. Part 1: General requirements
ISO 2631-2(1989)	Part 2: Continuous and shock-induced vibrations in buildings (1 to 80 Hz)
ISO 2631-4(2001)	Part 4: Guidelines for the evaluation of the effects of vibration and rotational motion on passenger and crew comfort in fixed-guideway transport systems
ISO 2631-5(2004)	Part 5: Method for evaluation of vibration containing multiple shocks

ISO 2631-1 defines the exposure limits for vibrations transmitted to the human body within the following frequency ranges:

a) 0.5 Hz to 80 Hz for health, comfort, and perception of vibration;
b) 0.1 Hz to 0.5 Hz for the prevention of motion sickness.

The main variables describing the measurement of whole-body vibration exposure are:

a) The vibration measurement directions (or measurement axes) are presented in Figure 4;
b) Measurement location;
c) Measurement duration.

Fig. 4 - Illustration of vibration measurement directions on the tractor and the operator

The vibrations transmitted to the human body must be monitored at the contact points between the body and the vibrating surface. These main contact areas may vary and are not always immediately apparent. According to ISO 2631-1, for seated persons, three main measurement zones are used:

- The vehicle floor (seat support surface and the contact surface of the operator's feet);
- The horizontal surface of the vehicle seat;
- The seat backrest.

The measurement duration must be sufficiently long to ensure adequate statistical accuracy and to accurately reflect the characteristics of the vibrations to which the operator is exposed. The vibration level, expressed as the root mean square (r.m.s.) value, represents the mean acceleration measured at the seat level during the operator's driving activity in the seated position. The analysis of mechanical vibrations involves measuring the weighted average acceleration, represented by the root mean square (r.m.s.), along the X, Y, and Z measurement axes. The formula used to calculate this value is expressed in Equation (1).

$$a_{w\,\text{r.m.s}} = \left[\frac{1}{T}\int_0^T a_w^2(t)dt\right]^{1/2} \quad (1)$$

where: $a_w^2(t)$ - is the frequency-weighted acceleration at time t;

T — is the measurement duration.

The overall magnitude of the oscillatory motion is determined using the formula expressed in Equation (2):

$$a_{W_v} = \sqrt{k_x\,a_{W_x}^2 + k_y\,a_{W_y}^2 + k_z\,a_{W_z}^2} \quad (2)$$

where: k_x, k_y și k_z represent multiplication factors applied to the measurement axes X, Y și Z.

To assess the impact of vibration exposure on human health, it is necessary to determine the frequency-weighted root mean square (r.m.s.) acceleration within the range of [0–80] Hz. This parameter must be measured for periodic, random, or transient vibrations transmitted to the human body in the seated position through the seat surface. According to ISO 2631-1, the Health Guidance Caution Zone (HGCZ) is defined based on this frequency-weighted acceleration, measured along the dominant Z-axis, and is illustrated in the red-highlighted area in Figure 5 *(de la Hoz-Torres, M. L. et al. 2022; Plewa, K. M. et al. 2012)*.

The Health Guidance Caution Zone (HGCZ) is based on the principle of energy conservation. Assuming that the human body's response is directly proportional to the total energy of the vibrations to which it is exposed, two different daily vibration exposures can be considered equivalent when the condition expressed by the formula in Equation (3) is satisfied.

$$a_{w1}T_1^{1/2} = a_{w2}T_2^{1/2} \quad (3)$$

where: a_{w1} şi a_{w2} – represent the frequency-weighted root mean square (r.m.s.) acceleration values corresponding to the first and second whole-body vibration exposures, respectively;

T_1 şi T_2 – represent the exposure durations corresponding to the first and second vibration events, respectively.

As reported in the specialized literature, the equation defined in Relation (4) reveals a time-dependent behavior:

$$a_{w1}T_1^{1/4} = a_{w2}T_2^{1/4} \quad (4)$$

Figure 5 illustrates the Health Guidance Caution Zone (HGCZ), as defined by the health-related indications derived from the application of Equations (3) and (4). This zone emphasizes the frequency range in which additional protective measures are required to prevent potential health risks.

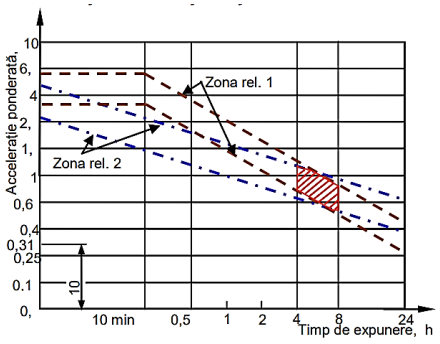

Fig. 5 - Health Caution Zone

At the end of this chapter, the process of experimental data acquisition concerning the vibrations transmitted to the driver is described, using accelerometer-type sensors from the Biometrics Ltd range [BIOM]. The measurement systems were configured to record the three-dimensional components of acceleration (X, Y, Z axes) at critical contact points (seat, backrest, and floor), in accordance with current international standards. The raw data obtained were processed using the specialized software VATS – Vibration Analysis ToolSet (NexGen Ergonomics), which provides advanced functionalities for spectral analysis, frequency weighting calculations according to ISO 2631-1, identification of dominant frequency components, and determination of root mean square (RMS) acceleration values.

The data acquisition system developed by Biometrics Ltd enables the collection of both analog and digital data from a wide range of sensors. The DataLog MWX8 equipment used in the study is illustrated in Figure 6 and represents a modern device capable of collecting experimental data at sampling frequencies of up to 20,000 Hz..

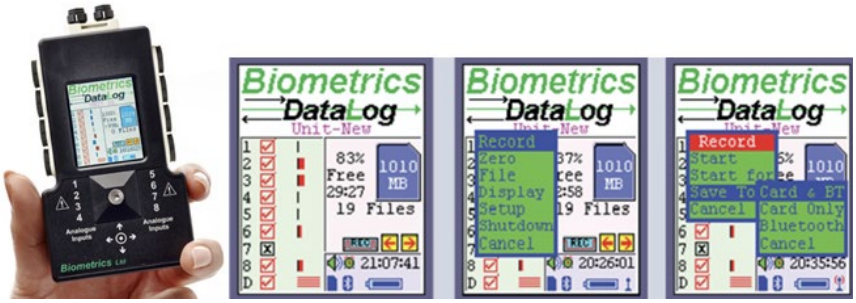

Fig. 6 - DataLog MWX8 data acquisition equipment (Biometrics Ltd)

The triaxial accelerometer sensors (illustrated in Figure 7) are high-precision 3-axis sensors rated at 10 G, featuring factory-set offset and sensitivity, thermal signal isolation, and adjustable filters for each channel. They connect directly to the DataLog data acquisition device, with each channel linked to the host instrument via a separate connector.

Fig. 7 - Triaxial accelerometer sensors from the Biometrics Ltd range used for vibration data acquisition

A vibration analysis toolkit used for data processing is VATS™ (Vibration Analysis Tool Set), developed by NexGen Ergonomics, which is designed for whole-body vibration analysis. The system integrates the MWX8 DataLog data acquisition unit, which collects data from accelerometer-type sensors. The interface of this software is presented in Figure 8.

The DataLog equipment includes a real-time clock, allowing each recording to be time-stamped with an exact start date and time, as well as its total duration. VATS performs whole-body vibration analysis for the health, comfort, and perception domains, in accordance with the ISO 2631-1 standard.

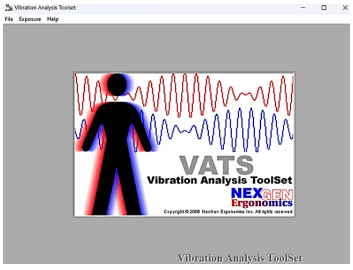

Fig. 8 - Software interface of NexGen Ergonomics VATS™ used for whole-body vibration analysis

RESULTS

This chapter presents the current research directions in the field of whole-body vibrations (WBV), with a focus on their influence on the human body, particularly in the context of operating agricultural

vehicles. The present study integrates relevant findings from the specialized literature published over the last decade, highlighting the progress made in biomechanical modeling of the human body, identification of critical resonance frequencies, analysis of physiological responses to vibrational exposure, and the development of professional risk assessment methodologies.

Recent research reflects a clear trend toward deepening experimental studies through the use of advanced measurement and simulation systems, as well as the application of international standards (ISO 2631-1, ISO 2631-5) as benchmarks for exposure quantification. In particular, the literature emphasizes the significant impact of vibrations generated by self-propelled agricultural vehicles, such as tractors, on the lumbar and spinal segments and the vestibular system, underlining the need for corrective measures regarding workstation ergonomics, seat suspension design, and exposure time management.

During the operation of various types of vehicles, vibrations are primarily generated by the interactions between the tires and the road surface. Several studies have been conducted to analyze the impact of vibrations on the driver, caused by different terrain types ranging from plowed fields to flat surfaces *(Singh, A. et al. 2019; Park, D.J. et al. 2019; Oncescu, T.A. et al. 2022; Oncescu, T.A. et al. 2024)*. Whole-body vibrations (WBV) transmitted to the driver represent one of the most influential factors affecting health and comfort, and the specialized literature documents numerous studies in which tractor operators are exposed to high levels of WBV and mechanical shocks *(Kabir, M. S. N. et al. 2015; Sun, L. et al. 2024; Cvetanovic, B. et al. 2017; Fethke, N. B. et al. 2022)*.

Exposure to high levels of vibration is associated with multiple health disorders, including musculoskeletal conditions such as lower back pain, as discussed in the studies by *(Bovenzi, M. et al. 2021; Jithendar, K. et al. 2023; Benos, L. et al. 2020)*, general muscle fatigue (Huang, Q.et al. 2023). Recent studies have also emphasized the psychological effects of vibration exposure, such as increased stress and anxiety levels, which can impair driver attention and operational performance *(Bhuiyan, M.H.U.et al. 2022; Vosoughi, S. 2019; Sorosh, A. 2019; Jalilian, H. et al. 2019; Johnson, P. W. et al. 2017)*.

Several specialized studies have addressed these safety concerns, with a primary focus on the technical design and performance characteristics of agricultural tractors *(Biris, S.S. et al. 2020; Ayers, P. et al. 2018)*, vibrations *(Vallone, M. et al. 2016)* and vehicle ergonomics *(Jamshidi, N. et al. 2016)*. Among these elements are the tractor cabin, tires and tire pressure, chassis, axles, and seat suspension systems, *(Choi, H.-J. et al. 2018; Deboli, R. et al. 2017; Poczwardowski, A. et al. 2022; Brusl, H. et al. 2021)*.

The specialized literature investigates how various types of running surfaces affect tractor operation *(Singh, A. et al. 2022; Cuong, D. M. et al. 2015; Zhang, J. et al 2022)*. The specialized literature has examined the behavior and posture of tractor operators through studies assessing whole-body vibration exposure, following the methodologies defined by specific international standards *(Caffaro, F. et al 2018; Irwin, J. D. et al. 2019; Fargnoli, M.et al. 2019)*.

Figure 9 illustrates the diagram of the geographical distribution of organizations and institutions involved in this field, contributing to the improvement of vehicle ergonomics, particularly for self-propelled agricultural vehicles such as tractors.

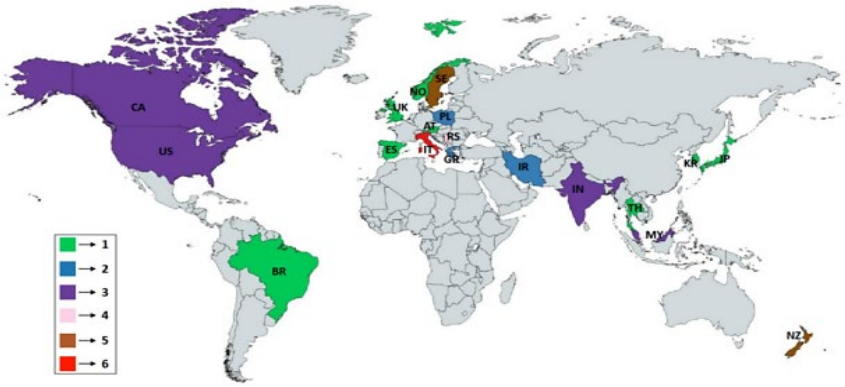

Fig. 9 - Geographical distribution of research organizations contributing to vehicle ergonomics improvement

CONCLUSIONS

This review article has provided a comprehensive and structured analysis of the specialized literature concerning the influence of vibrations on the human body, with particular emphasis on drivers of self-propelled agricultural vehicles such as tractors. Through a rigorous documentation of vibration sources

and their transmission phenomenology to the human body, the study highlighted the critical resonance frequencies and their implications for operator health. A systematic presentation of the main methodological approaches for evaluating whole-body vibration exposure levels was achieved, complemented by a detailed description of the equipment and procedures used for the acquisition and processing of relevant experimental data.

The current state of research in the field of Whole-Body Vibrations (WBV) has been outlined, emphasizing development trends, persistent scientific gaps, and the need for interdisciplinary approaches. This review contributes to strengthening the theoretical and practical framework required for the development of effective strategies for monitoring, prevention, and ergonomic optimization in the field of occupational vibration exposure.

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THE INFLUENCE OF STORAGE CONDITIONS ON THE QUALITY OF CANNED MEAT
/
INFLUENȚA CONDIȚIILOR DE DEPOZITARE ASUPRA CALITĂȚII CONSERVELOR DE CARNE

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ABSTRACT
The objective of this study was to evaluate the quality of the canned beef, which was stored under four temperature conditions for a period of 14 days. The samples were analyzed at three distinct time points (Day 1, 7, and 14), namely at temperatures of 4-25°C (manufacturer's recommendation), 0-8°C, -16°C, and 44±1°C respectivelly, to simulate improper transport and storage conditions. For all these temperature regimes, physico-chemical analyses were performed, including the determination of pH, easily hydrolyzable nitrogen (EHN), water activity (a_w), total nitrogen, nitrite and nitrate content, fat oxidation by the Kreiss reaction, the presence of ammonia with Nessler's reagent, along with organoleptic analysis. The results showed a significant increase in easily hydrolyzable nitrogen content, especially at extreme temperatures (-16°C and 44°C), suggesting a degradation of the protein fractions. The study demonstrated that storage temperature have a direct impact on the quality of canned meat products, leading to accelerated degradation of the nitrogen compounds when stored outside of recommended conditions.

REZUMAT
Obiectivul prezentului studiu a constat în evaluarea calității conservelor de carne de vită care au fost depozitate în condiții diferite de temperatură, pe o perioadă de 14 zile. Probele au fost analizate la trei momente distincte (ziua 1, 7 și 14), în condiții de depozitare la 4-25°C (recomandarea producătorului), precum și la 0-8°C, -16°C și 44±1°C, pentru a simula un transport și o depozitare necorespunzătoare. Pentru aceste regimuri de temperatură au fost efectuat analize fizico-chimice, incluzând determinarea pH-ului, azotului ușor hidrolizabil (AUH), activității apei (a_w), azotului total, conținutului de nitriți și nitrați, a oxidării grăsimilor, a amoniacului cu reactiv Nessler, alături de analiza organoleptică. Rezultatele au evidențiat o creștere semnificativă a conținutului de AUH, în special la temperaturile extreme (-16°C și 44°C), sugerând o degradare a fracțiunilor proteice. Studiul a demonstrat că temperatura de depozitare are un impact direct asupra calității conservelor, ducând la o degradare accelerată a compușilor cu azot, în condiții de depozitare diferite de cele recomandate.

INTRODUCTION
Preservation of meat is a fundamental process in the food industry, with a long history, which has evolved from traditional methods to complex technologies, essential for ensuring global food security and market diversification *(Sholpan et al., 2022).* Canned meat is a stable product on the shelf, the quality and safety of which critically depends on the maintenance of integrity throughout the entire life cycle, from production to the consumer *(Haouet et al., 2018).*

The shelf life of a food product defines the period during which it retains its sensory, chemical, physical and microbiological characteristics to an acceptable level while remaining safe for consumption *(Torrieri et al., 2016).* This term is influenced by a multitude of intrinsic (product composition, pH, water activity) and extrinsic (temperature, humidity, light) factors *(Simpson et al., 2012).* Among extrinsic factors, temperature is considered the most important parameter, since it governs the speed of most chemical and biochemical degradation reactions *(Mizrahi et al. 2004).* Despite manufacturers' recommendations for specific storage conditions, typically a dry and cool environment (4-25°C), products are often subjected to unsuitable conditions during transit and subsequent storage, including at the final consumer stage.

The quality and freshness of meat products are closely related to the proportion of nitrogen fractions. Total nitrogen (N_T) is an indicator of the general protein content, while EHN, which includes low molecular weight compounds such as ammonia, amines and free amino acids, represents a sensitive indicator of the

proteolysis processes *(Simpson et al., 2012, Khalid et al., 2022).* An increase in the content of EHN indicates a degradation of the protein structure and, implicitly, a loss of the nutritional and sensory quality of the product *(Motoc et al., 1966).*

The mechanisms by which proteinaceous compounds degrade at extreme temperatures are well-documented in the scientific literature. High temperatures accelerate thermal protein denaturation and residual enzymatic reactions *(Khalid et al., 2022).*

In contrast, frost, although it slows most chemical reactions, induces severe mechanical stress on the structure of the meat product. The formation of ice crystals in the product matrix leads to the physical destruction of muscle fibers, the release of previously bound water in protein structures, and the exposure of proteins to the action of endogenous enzymes, which can lead to accelerated post-defreezing degradation *(Kuznetsova et al., 2022).* However, the impact of such short term stress conditions on the chemical stability of canned meat is a less explored area.

The objective of this study was the quantitative assessment of the evolution of nitrogen fractions and several other associated parameters in canned beef, subjected for 14 days to storage conditions that simulate non-compliant scenarios (refrigeration, freezing, and exposure to high temperatures), compared to standard ones.

MATERIALS AND METHODS

Samples of canned beef in its own juice were utilised in this study. To ensure the homogeneity of the experimental material and the comparability of findings, all samples were sourced from a single production batch, with all units sharing identical identification data, such as the batch number, manufacturing date, and best-before date.

The study was designed to evaluate the impact of four different storage conditions over a period of 14 days on some relevant physical-chemical parameters, including the nitrogen-related characteristics of canned meat. The samples were stored under the following conditions: in a dry and cool place at a temperature between 4 and 25°C, as recommended by the manufacturer; under refrigeration at 0–8°C; under freezing conditions at a temperature of -16°C; and at a controlled high temperature of 44±1°C.

Analyses were carried out at three different time points to observe the evolution of the quality parameters: T1 (day 1), T2 (day 7), and T3 (day 14). Standard analytical methods were applied to evaluate the changes, as detailed in the specialized literature. pH determination was carried out directly on the homogenized sample, utilizing a digital pH-meter equipped with a penetration probe suitable for semi-solid products. Water activity (a_W) determination involved the measuring of the a_w value with a water activity analyzer, by placing the homogenized sample into the equipment's measuring crucible.

For the easily hydrolyzable nitrogen determination, the method was based on the release of volatile nitrogenous compounds through steam distillation in the presence of magnesium oxide.

The liberated ammonia was captured in a boric acid solution and subsequently titrated with a 0.1 N hydrochloric acid solution. Total nitrogen (N_T) determination employed the standard Kjeldahl method, which encompasses three stages: sample mineralization with concentrated sulfuric acid in the presence of a catalyst, ammonia distillation after alkalization, and titration of the distillate. The total protein content was calculated using the standard conversion factor of 6.25. Nitrite and nitrate determination involved the Griess spectrophotometric method.

This method relies on the diazotization reaction in an acidic medium and the formation of a coloured compound, whose absorbance was measured at 520 nm. To complete the quantitative evaluation, qualitative analyses were also performed: organoleptic analysis consisted of an assessment of the samples' sensory characteristics, including the can appearance, as well as the appearance, taste, and smell of the meat, according to a standard evaluation grid. Fat oxidation determination is based on the qualitative Kreis reaction to detect the presence of aldehydes, which are secondary products of oxidative rancidity.

Finally, the ammonia identification, as an indicator of advanced degradation of proteins, was verified through the qualitative Nessler reaction.

All quantitative determinations were performed in duplicate. The results were presented as mean, and for the EHN and the protein content, as mean ± the calculated uncertainty value.

RESULTS

General product stability: qualitative and organoleptic analysis

The qualitative evaluation of the samples of canned beef during the 14 days of study revealed a noteworthy stability from a sensory point of view. Regardless of the storage conditions, all samples showed normal organoleptic characteristics and complied with the product specifications and legal requirements: intact, non-swollen can, as well as specific appearance, colour, taste and smell. In addition, the qualitative tests to detect degradation were negative in all cases.

No evidence of fat oxidation was detected by the Kreiss reaction, and the absence of free ammonia - a marker of advanced spoilage - was confirmed using Nessler's reagent.

These results suggest that, at the macroscopic and sensory level, the product maintained its quality during the experiment, even under severe thermal stress. However, this apparent stability contrasts with the measurable chemical changes discussed in the following sections. It is important to outline that the protein and other chemical compounds degradation may reach chemically significant levels before the product becomes organoleptically unacceptable to the consumer.

This discrepancy highlights the limitations of sensory analysis as the only quality control tool and validates the need for the use of chemical markers, which are much more sensitive and are recommended as early indicators of quality loss for the meat products. In terms of the food industry, this implies that the assessment of the impact of an incident in the cold chain (for example, a failure of the cooling system) or the establishing of a realistic shelf life should not be based solely on sensory tests, but requires a complementary quantitative physico-chemical approach.

Changes in the physical-chemical matrix: pH and water activity (a_w)

Changes within the internal environment of the studied canned beef, reflected by the pH and water activity, provide valuable information about the degradation processes. The data obtained are summarised in Table 1.

Table 1

Change in pH and water activity (aw) depending on storage conditions and time

Storage conditions	Time point	pH	Water activity (a_w)
Control (4-25 °C)	T1	6.15	0.928
	T2	6.16	0.925
	T3	6.11	0.927
Refrigeration (0–8°C)	T2	6.15	0.942
	T3	6.24	0.954
Freezing (-16°C)	T2	6.18	0.956
	T3	6.15	0.962
High Temperature (44±1°C)	T2	6.15	0.957
	T3	6.13	0.961

A general trend of slight acidification (decrease in pH) is observed in most samples of canned beef, a phenomenon that can be associated with the slow continuation of Maillard-type reactions or the partial hydrolysis of the meat components, with acid formation. A notable exception is the samples stored at 0-8°C, in which the pH rises to T3 up to the value of 6.24. This increase in pH is probably the result of the activity of psychrotrophs, which, although slowed down by the cold, can continue to break down proteins, releasing amines and ammonia *(Triki et al., 2018).*

The most significant change is noticed for the water activity. The canned beef samples subjected to extreme conditions, both freezing (-16°C) and high temperature (44°C), show a sharp increase in the value a_w, reaching 0.962 and 0.961 at the end of the study, respectively. This increase should not be seen as a simple effect, but an active factor in the process of degradation.

Thermal stress, either by heat or by the mechanical action of ice, induces proteins denaturation in the meat matrix and leads to the relaxation of their tertiary and quaternary structure and the release of water that was previously "bound" inside these structures *(Kerth et al., 2013).*

The released water increases the "free" fraction of the system, which is measured by a higher a_w value. The increased water activity signifies a greater molecular mobility and increased availability of water as solvent and reactant, creating a more favourable environment for further acceleration of hydrolytic

reactions such as proteolysis. This establishes a causal relationship, namely the thermal stress causes protein distortion, which leads to increased a_w, which in turn accelerates other degradation reactions.

Nitrogen faction degradation: easily hydrolyzable nitrogen (EHN) and total nitrogen (N_T)

The analysis of nitrogen fractions provides a direct picture of protein integrity. The results are presented in Table 2.

Table 2

Evolution of protein and easily hydrolyzable nitrogen

Storage conditions	Time point	Protein	Easily hydrolyzable nitrogen
		[g/100g]	[mg/100g]
Control (4-25 °C)	T1	11.93±0.33	29.63±1.66
	T2	12.08±0.34	29.67±1.66
	T3	12.22±0.34	31.61±1.77
Refrigeration (0–8°C)	T2	11.99±0.34	30.56±1.71
	T3	12.32±0.35	35.08±1.96
Freezing (-16°C)	T2	11.82±0.33	42.00±2.35
	T3	11.79±0.33	45.57±2.55
High Temperature (44±1°C)	T2	12.08±0.34	33.31±1.87
	T3	12.21±0.34	36.69±2.05

The protein content, determined from total nitrogen, was relatively constant, indicating that the total nitrogen, in all its forms present in the product, constituted a closed system. In contrast, the evolution of easily hydrolyzable nitrogen is dependent on storage conditions. At 44°C, the EHN content increases by about 24% from the initial value, an explainable result due to the thermal acceleration of the hydrolysis reactions *(Krylova et al., 2017)*.

The most significant finding was the over 50% increase in EHN content in the samples stored at -16°C. This apparently counterintuitive phenomenon does not reflect the intense chemical activity at freezing temperature but rather highlights a distinct degradation mechanism initiated by a physical factor. The formed ice crystals cause irreversible mechanical damage to muscle fibres *(Kuznetsova et al., 2022)*.

This structural damage exposes numerous normally protected cleavage sites. When the sample is analyzed at room temperature, these vulnerable proteins hydrolyze much more easily. Therefore, the high EHN value at -16°C quantifies the increased vulnerability to degradation induced by the physical stress of freezing.

The evolution and stability of nitrites and nitrates

Nitrites and nitrates are essential additives in meat products, with a role in stabilising colour, flavour and inhibiting the growth of the pathogenic bacteria *Clostridium botulinum (Banu, 2022, Chira et al, 2005)*, therefore their stability is crucial to the safety of the product (Table 3).

Table 3

Monitoring the content of nitrites and nitrates during storage

Storage conditions	Time point	Nitrites	Nitrates
		[mg/kg]	**[g/100g]**
Control (4-25 °C)	T1	10.90	2.89
	T2	10.91	3.21
	T3	10.97	3.29
Refrigeration (0–8°C)	T2	10.90	1.10
	T3	10.97	1.94
Freezing (-16°C)	T2	10.88	2.38

Storage conditions	Time point	Nitrites	Nitrates
		[mg/kg]	[g/100g]
	T3	12.63	3.58
High Temperature (44±1°C)	T2	10.74	1.49
	T3	12.51	1.76

It can be noticed that an increase in nitrite concentration to T3 is observed in samples subjected to heat stress (-16°C and 44°C), while nitrates exhibit wide fluctuations. These variations suggest that thermal stress disrupts the chemical balance of the conservation system. The increase in nitrites concentration could be the result of the decreasing of residual nitrates by thermostable microbial enzymes or by non-enzymatic chemical reactions.

Regardless of the overall mechanism affecting the quality of canned meat products during storage, the instability of this system has implications for long-term food safety of canned meat. Uncompliant storage could compromise secondary chemical barriers that inhibit the development of heat-resistant spores *(Wang et al., 2020).*

CONCLUSIONS

According to the analysis carried out over a period of 14 days in non-compliant scenarios, the evolution of nitrogen fractions and other relevant quality indicators in meat cans reveals relevant aspects that could be exploited to be further recommmended for industrial practices. As regards the total nitrogen, there was an insignificant variation in its content regardless of storage conditions. This result indicates the noteworthy protein stability during the 14 days of the study, suggesting that the nutritional integrity of the product is well maintained under the simulated conditions.

The analysis of water activity revealed a direct correlation with storage temperature. It has been observed that water activity increases at higher temperatures and decreases at lower temperatures, which is a crucial aspect for food stability and safety, as high levels of water can favour microbial growth and degradation reactions. Regarding the nitrite and nitrate content, the study showed significant variations depending on storage conditions.

Fluctuations in their concentration can be associated with different rates of chemical conversion and degradation, influenced by the temperature and humidity of the environment. A positive finding was obtained from tests to identify ammonia with the Nessler reagent and fat oxidation by the Kreis reaction, both of which yield negative results.

This finding is very relevant in terms of food quality and safety, as the absence of ammonia and signs of oxidation confirms that the stability of the product is maintained during the experiment. EHN levels showed significant variations depending on storage conditions.

Although there were notable differences between samples, the highest value of 45.57 mg/100 g was obtained at time point T3 in the case of beef can stored at -16 °C. This value is below the maximum permissible limit of 55 mg/100 g, as specified in Romanian Order No. 560/2006 from the Ministry of Agriculture, Forests and Rural Development.

While higher levels of EHN suggest possible product degradation or changes, careful monitoring of this parameter is recommended to ensure the quality and safety of canned foods, in particular the canned meat products.

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STUDY ON OPTIMIZING THE PERFORMANCE OF ROW CROP SEEDERS
/
STUDIU PRIVIND OPTIMIZAREA PERFORMANȚELOR SEMĂNĂTORILOR DE PLANTE PRĂȘITOARE

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Keywords: *automated system, seeding depth control, row crops*

ABSTRACT

This paper presents a study aimed at designing an automated seeding depth control system for row crop seeders, ensuring the optimal and uniform placement of seeds in the soil, with real-time adjustments directly from the tractor cabin. The intelligent system will be adapted to variable soil conditions, maintaining consistent optimal germination conditions across the entire working width. The row crop seeder equipped with this automated system will provide precise seed placement at recommended agrotechnical depths, promoting uniform emergence and maximizing crop yields. Such a system is essential for modern farms utilizing precision agriculture to optimize agricultural processes.

REZUMAT

Lucrarea cuprinde un studiu realizat în scopul proiectării unui sistem automat de control al adâncimii de semănat la mașinile de semănat plante prășitoare, pentru a asigura plasarea semințelor la o adâncime optimă și uniformă în sol, în timp real direct din cabina tractorului. Sistemul inteligent va fi adaptat la condițiile variabile ale solului, asigurând aceleași condiții optime de germinare pe întreaga lățime de lucru. Semănătoarea de plante prășitoare echipată cu acest sistem automat va asigura o plasare precisă a semințelor la adâncimi agrotehnice recomandate, favorizând o răsărire uniformă și maximizând randamentului culturilor. Un astfel de sistem este esențial pentru fermele moderne care folosesc agricultura de precizie pentru optimizarea proceselor agricole.

INTRODUCTION

Global food production is facing profound challenges due to complex factors such as population growth, climate change, a condensed period of multiple crises (e.g. wars, geopolitical conflicts and pandemic effects) and changing consumer preferences *(Galanakis, C.M. 2020; Galanakis, C.M. et al., 2021; Galanakis, C.M., 2023).*

For example, the world population is projected to reach approximately 9.7 billion by *2050 (Bahar, N.H. et al, 2020)*, requiring resource management and creating an increasingly urgent need for the production of safe, nutritious and sustainable food.

The rapid growth in global food demand is accompanied by urbanisation, a corresponding increase in environmental impacts and the expansion of agriculture, all of which require the sustainability and resilience of our food systems *(Boyaci-Gunduz, C.P. et al., 2021; Tilman, D.; Balzer et al., 2011).*

Agriculture, as the main source of sustainable food, is significantly affected by climate change and extreme weather events, such as temperature variations, erratic rainfall and the availability of surface and groundwater resources *(Markou, M. et al., 2020).*

As the population grows, it is essential to improve food production. Technological advancement is crucial for the agricultural sector to minimise the conventional seeding process and produce high quality food products to better meet the basic food needs of humanity *(Bhujangarao, A. et al., 2023).* Seed drills are specialized agricultural equipment designed for precision seeding of various row crops such as corn, sunflower, soybean, sugar beet, etc.

These machines are at the heart of the seeding process in agriculture and play a critical role in crop yield and efficiency *(Yadav, N.K. and Meena, S.S., 2024).* The most commonly used seed drills today are pneumatic seed drills, which use an air pressure system to distribute the seed. The distributors are driven by

the drive wheel through various transmission components such as chains, gears, shafts and belts *(Soyoye, B. O., 2020)*.

Figure 1 shows the functional diagram of a row crop planter (precision sowing of crops such as maize, sunflower, etc.). The planter is of the pneumatic type *(Cujbescu, D. et al., 2022; Marin, E. et al., 2010)*.

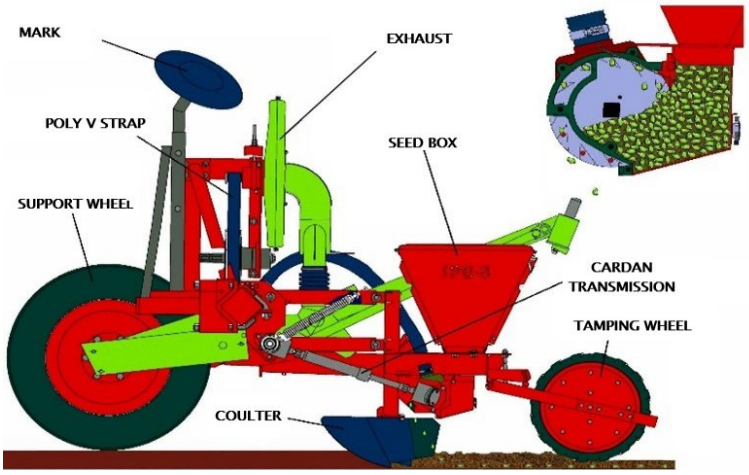


Fig. 1 - Functional diagram of a row crop seeder

During operation, the exhaust fan creates a vacuum which is transferred to the seed distribution units via suction tubes. The vacuum holds the seed in the supply chambers against the openings of the distributor discs. As the row planter moves, the support wheels transmit motion through a gearbox with sprockets and cardan shafts to the distributor shafts which rotate the discs, sending the seeds into the furrows and from there into the open grooves created by them. Only one seed is fixed to each disc hole due to the limited space around the hole. The packer wheels close the furrows and compact the soil to the sides of the planted row. The planter is guided across the field by the tracks left on the ground by the marker *(Bahar, N.H. et al.; 2020)*.

Ensuring uniform distribution along the row within the specified interval, minimizing seed damage, accurate dosing regardless of travel speed, and proper seed placement at the correct depth of the furrow are current requirements aimed at improving the quality indicators of crop sowing *(Zahariev, I. and Kehayov, D., 2022)*.

The utilization of row crop planters (corn, sunflower) in contemporary agriculture is imperative, as they facilitate precise seed distribution, optimize row spacing, and promote the cultivation of uniform crops, thereby fostering high and efficient yields *(Nielsen, S. K., et al., 2018)*.

Precision pneumatic seeders, which are instrumental in ensuring optimal crop germination, must place seeds with exactitude at the depth where soil moisture is present to facilitate seed germination *(Thalmann, G., 1983)*.

The current stage in monitoring and controlling sowing depth involves research aimed at using sensors to control sowing depth in real time, allowing for automatic adjustments directly from the tractor cabin. This system integrates with moisture sensors, such as the Correvit-H400/250, manufactured by Pessl Instruments, to ensure that seeds are placed at optimal depths with adequate moisture. The overarching objective of these systems is to minimize variability between rows and ensure uniform sowing depth across the entire field *(Iqbal, T. et al, 2022; Li, Y. et al., 2015)*.

International companies with a reputation for innovation, such as Ag Leader, have developed advanced technology to optimize the down Force of seeders during operation using the ISOBUS Hydraulic Down Force Row Module Detection. Utilizing the SureForce sensor, this technology instantly provides the necessary downforce to maintain depth in no-till conditions and across different soil types, through heavy residues and compacted areas. This technology is part of a broader trend in agriculture of automation and digitalization, which is having a significant impact on efficiency and productivity *(Zhou, L. et. Al., 2023)*.

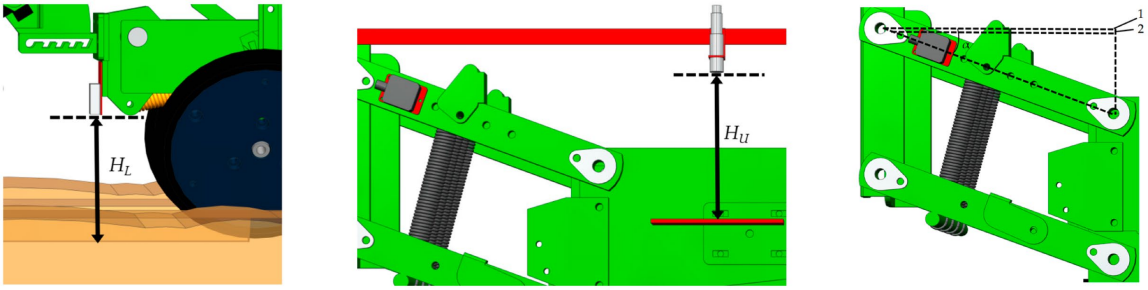
Ag Leader Technology, Inc. is a recognized leader in the field of precision farming hardware and software. Headquartered in Ames, Iowa, USA, the company specializes in the design, manufacture and marketing of precision technology, with the objective of assisting farmers in making informed decisions that

lead to profitable outcomes. Since its establishment in 1992, the company has experienced consistent growth and expansion by offering products that provide added value to farmers, thereby contributing to their sustained profitability. Further information can be found at www.agleader.com.

In a move that exemplifies its commitment to innovation, John Deere has developed FurrowVision™, a state-of-the-art technology integrated into its planter seeders. This technology is designed to enhance the precision and efficiency of the seeding process by verifying seed depth and providing a visualization of the seeding channel directly from the tractor cab. This is achieved by incorporating a video camera within the actual plant furrow. This technology focuses on monitoring and controlling planting depth and seed positioning in seed rows, ensuring uniform and optimal germination *(https://www.futurefarming.com/crop-solutions/john-deere-announces-furrow-vision/).*

The implementation of precision sowing technology, which involves the meticulous adjustment of sowing depth, necessitates the integration of sensors of various types, along with PID (Proportional Integral Derivative) controllers. These controllers are instrumental in ensuring the seamless operation of automation and control systems, where they function as critical components in maintaining process values within the desired range.

The sensors, which can be classified as laser, ultrasonic, or angle types, can be mounted in different positions on the sowing section (Fig. 2, a, b, and c) *(Wang, S. et al., 2024).*



a. b. c.

Fig. 2 - Diagrams of the sensor detection principle in the seeding depth control system
a. Principle of monitoring with a laser sensor; b. Principle of monitoring with an ultrasonic sensor; c. Principle of monitoring with an angle sensor, 1. Horizontal plane. 2. Initial height
(Wang, S. et al., 2024)

The following table presents the main characteristics of the sensor types.

Table 1

Main parameters of the sensors used

Sensor type	Parameter	Value
Laser sensor	Measurement accuracy/mm	0.5
	Measurement range/m	0.05~80
	Spot size/mm	6
Ultrasonic sensor	Beam angle/(°)	10
	Detection range/cm	7~100
	Blind measurement zone/cm	0~7
Angle sensor	Measurement resolution/(°)	0.01
	Measurement accuracy/(°)	0.05
	Measurement range/(°)	±90

Recent research endeavours have culminated in the formulation of intelligent seeding systems that leverage artificial intelligence and optimisation algorithms to dynamically adjust seeding depth in real time. Precision Planting is recognised for its innovations in agricultural technologies, which assist farmers in improving the accuracy and efficiency of seeding, fertilisation and crop monitoring.

Utilising advanced sensors, electronic control systems and data analytics, the company provides solutions that optimise resource utilisation and enhance crop yield. One such example is the SmartDepth™ *(https://www.precisionplanting.com/products/planters/smartdepth)* system, which integrates advanced sensors and an automated control system to optimise seed placement based on soil conditions. A second example is DeltaForce® coulter pressure control, which optimises the force applied to the seeding unit to maintain a constant seed depth in any soil type *(Cloete, S., 2019).*

The sections of precision pneumatic seed drills are mounted to the frame bar by means of a deformable parallelogram mechanism, and to control the sowing depth they are provided with different mechanisms for adjusting the pressing force of the depth wheel drive system (see Figures 3a, b and c) *(Li, H. et al., 2023)*.

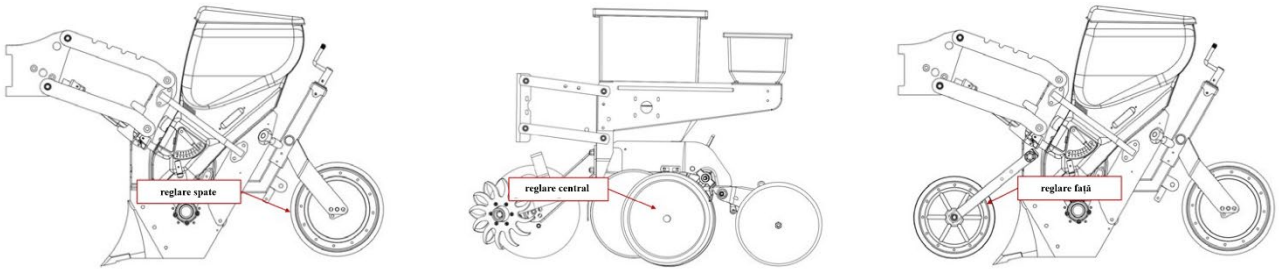
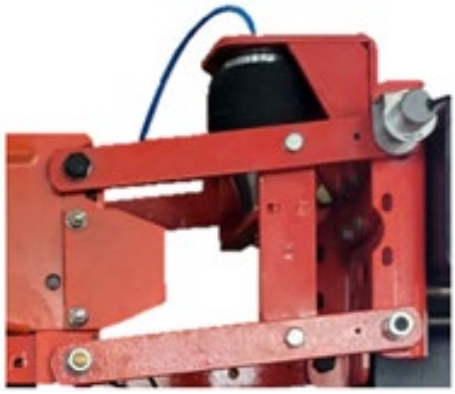


Fig. 3 - Downforce adjustment mechanisms for the depth wheel drive system
a. Rear adjustment mechanism; b. Central roller adjustment mechanism; c. Front adjustment
(Tilman, D. et al., 2011)

The pressing force adjustment mechanism of the passive type depth wheel drive system primarily employs a mechanical spring, while the pressing force adjustment mechanism of the active type depth wheel drive system predominantly utilises a hydraulic drive or a pneumatic drive, as illustrated in Table 2 *(Li, H. et al., 2023)*.

Table 2

Common methods of the downforce adjustment mechanism for the depth wheel system

Type	Partial view	Description
Mechanical adjustment		- Simple structure, high reliability, wide range of applications; - Easy to install and adjust; - Preload must be empirically adjusted based on soil conditions before operation; unstable aerodynamic force on the soil.
Hydraulic adjustment		- Requires sensor-assisted adjustment; - Complex structure; - Fast response time, suitable for high-speed operation; - Provides greater force and torque, adjustable range, and high stability.
Pneumatic adjustment		- Requires sensor-assisted adjustment; requires an external air supply unit; - Can withstand very high pressure and vibration impact; - Good vibration damping effect; high stability for seed drop.

MATERIALS AND METHODS

The research undertaken for the design of an intelligent control and monitoring system for the sowing depth was conducted on a seeder equipped with sowing sections procured from S.C. Mecanică Ceahlău S.A. Piatra Neamţ. The sowing sections are mounted to the frame bar by means of a system of articulated bars and a plate that is fixed to the square bar with two clamps. The sowing sections are equipped with a seed hopper, a pneumatic distribution device, a skid coulter, a zero-pressure tire compaction wheel and a chain transmission mechanism.

The compaction wheel shaft is capable of mounting four sprockets (z=9, z=10, z=11, z=16), while the distributor shaft can accommodate two sprockets (z=22, z=30). The configuration of the seeder ensures the accurate and consistent sowing of grains at regular intervals. This is facilitated by the pneumatic-mechanical distributor, which enables precise distribution, and the uniformity of the sowing depth is ensured by the left and right support wheels, which are supported on the frame bar by means of arms. The seed distributor transmission and the tamping wheel, equipped with a 0-pressure tire and a V-profile, ensure the conditions for optimal sowing. Figure 4 shows the main components of the equipment for sowing weed plants.

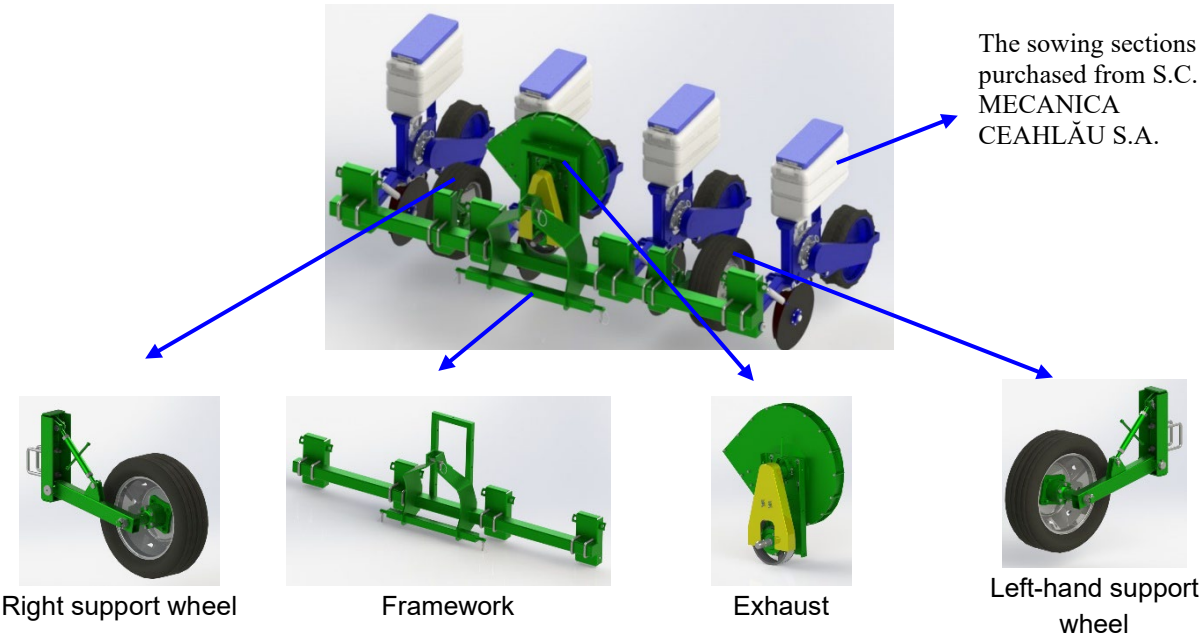


Fig. 4 - Main components of the row crop seeding machine

The working depth adjustment of the seed drill is accomplished through the utilisation of a double-threaded tie rod (equipped with two opposite threads, one on the right and one on the left), which facilitates the elevation or depression of the support wheel on the right or left side relative to the ground level. Consequently, the position of the coulter undergoes a proportional alteration, and the effective working depth is derived from the adjustment made. The soil settlement, estimated at 2-3 cm (due to the wheel sinking into the ground), is then subtracted from this.

The initial phase of this study involved the identification of contemporary solutions for replacing the double-threaded tie rod, thereby enabling automation of the working depth adjustment process through the integration of an intelligent control and monitoring system.

The following solutions are proposed:

- The electro-hydraulic system with depth sensors will consist of the following main components:
  - The double-threaded tie rod is replaced by an electronically controlled hydraulic cylinder.
  - Depth sensors (e.g. ultrasonic or LIDAR sensors) measure the position of the coulters relative to the ground in real time.
  - The hydraulic cylinder's optimal operating depth is automatically regulated by the control unit.
  - It is possible to integrate this with tractor ISOBUS systems for the purpose of in-cab control.
- The electric motor system with linear actuator will comprise the following main components:

- The installation of an electric actuator in lieu of the tie rod facilitates precise adjustment of the working depth.
- The implementation of intelligent software control facilitates the adjustment of the coulter position, a function that is informed by the readings received from the sensors.

In the final stage of this study, three-dimensional geometric models of the primary subassemblies, i.e. the constituent elements of the seeder for grass seeds, were developed. The Workstation 22H2, equipped with an Intel(R) Xeon(R) W-2123 CPU @ 3.60GHz, was utilized for this purpose. The parametric design program SOLIDWORKS® Premium 2018 S.P. 0.1 was used for 3D modelling.

Initially, each component was modelled in three dimensions individually, and subsequently assembled using the Assemblies module.

RESULTS

As illustrated in Figure 6, both support wheels are equipped with a hydraulic cylinder of the CS00503220 type, manufactured by Hidraulica Industrial *(https://hidraulica-center.ro/toate-produsele/cilindri-hidraulici/dubla-actiune/cilindri-cs/).*

Fig. 5 - Left support wheel

Fig. 6 - Right support whee

Figure 7 presents the functional diagram, and Table 3 details the primary parameters of a hydraulic cylinder of type CS00503220.

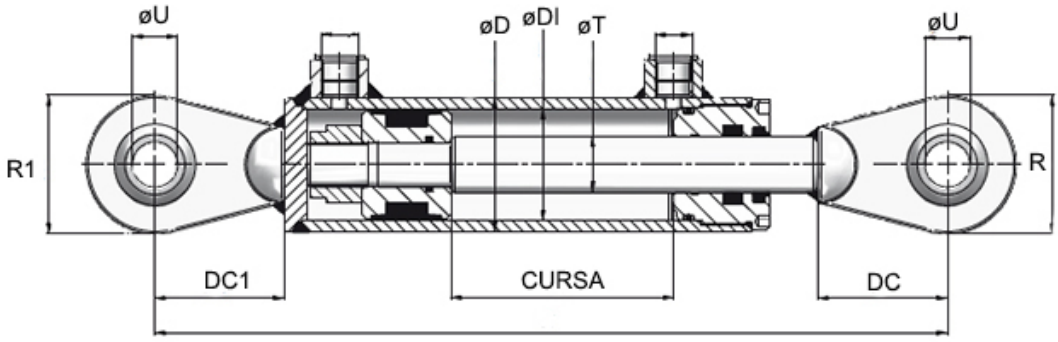


Fig. 7 - Functional diagram of a hydraulic cylinder type CS00503220

Table 3

Main parameters of the hydraulic cylinder type CS00503220

Cod	D	DI	T	Cursa	LT	U	R	DC	R1	DC1	F
CS00503220	42	32	20	50	275	16	46	60	46	60	¼”

As illustrated in Figure 8, the equipment for sowing weedy plants comprises two support wheels, each equipped with a hydraulic cylinder type CS00503220.

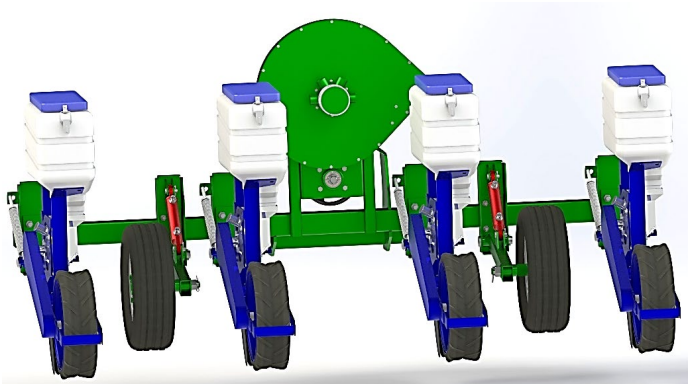


Fig. 8 - Row crop seeding machine equipped with a left support wheel and a right support wheel, each fitted with a hydraulic cylinder type CS00503220

As illustrated in Figures 9 and 10, each support wheel is fitted with a CONCENTRIC LACT4P-12V-20 linear electric actuator manufactured by Pololu Robotics and Electronics *(https://www.pololu.com/).*

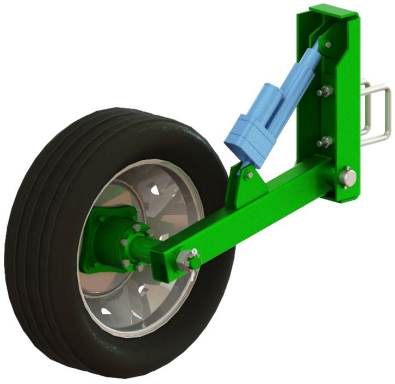


Fig. 9 - Left support wheel

Fig. 10 - Right support wheel

Figure 11 shows the diagram with the main dimensions, and table 4 shows the main parameters of a linear electric actuator type LACT4P-12V-20.

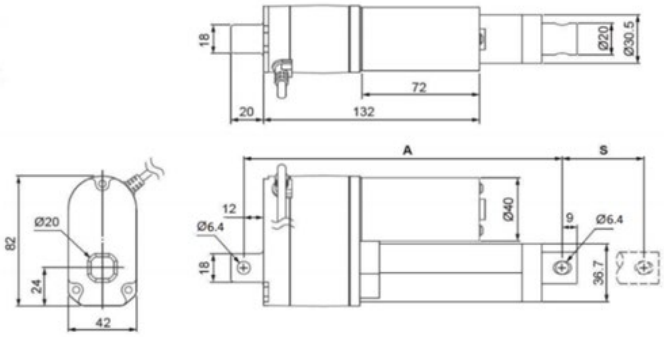


Fig. 11 - Diagram with the main dimensions of a linear electric actuator type LACT4P-12V-20

Table 4

Main parameters of the linear electric actuator type LACT4P-12V-20

Cod	Cursa S, mm	Lungimea retasă A, mm	Viteza de lucru, mm/s	Viteza de lucru în sarcina, mm/s
LACT4P-12V-20	100	246	14,6	12,3

Figure 12 presents a schematic illustration of the apparatus employed for the cultivation of weedy vegetation, consisting of the left and right support wheels, with each being equipped with a linear electric actuator designated LACT4P-12V-20.

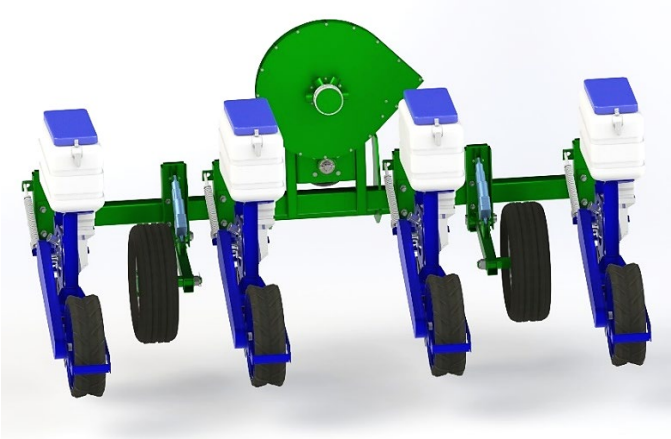


Fig. 12 - Row crop seeding machine equipped with a left support wheel and a right support wheel, each fitted with a linear electric actuator type LACT4P-12V-20

The automation of the CS00503220 hydraulic cylinder for seeding depth control encompasses the following components:

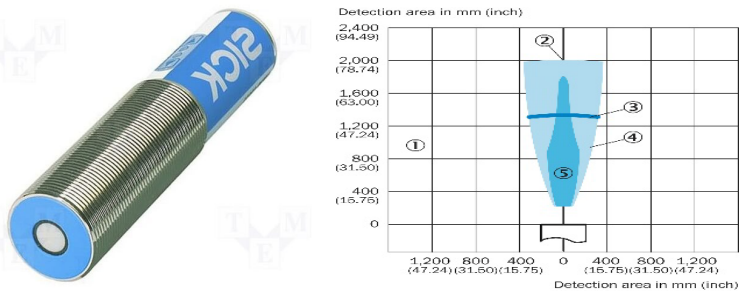
1. The Danfoss PVG 32 proportional hydraulic distributor (cf. fig. 13) is a device that regulates the oil flow to the cylinder depending on the signal received from the control unit.

Fig. 13 - Danfoss PVG 32 proportional hydraulic valve distributor
(https://lyra.ro/produs/distribuitor-danfoss-pvg-32-o-sectiune-proportionala-flotanta/)

2. The Temposonics MH magnetostrictive cylinder position sensor (see Figure 14) is a device that measures the position of the cylinder piston and transmits a signal to the control unit.

Fig. 14 - Temposonics MH magnetostrictive position sensor for cylinders
(https://www.infinitrade-romania.ro/produs/marcicomercializate/mts-sensors/senzori-de-pozitie-hidraulica-mobila-mts/senzor-de-pozitie-aplicatii-hidraulice-mh-mts/)

3. The distance sensor (ultrasonic/laser) quantifies the actual distance between the sowing unit and the ground, compensating for unevenness. The SICK UM30-213113 sensor (fig. 15) is a viable option, manufactured by SICK AG, a German company specialising in industrial sensors, automation and measurement systems.



① Detection range dependent on reflection properties, size, and alignment of the object
② Limiting range
③ operating range
④ example object: aligned plate 500 mm x 500b mm
⑤ example object: pipe with 27 mm diameter

Fig. 15 - SICK UM30-213113 distance sensor

(https://www.sick.com/cl/en/catalog/products/distance-sensors/ultrasonic-distance-sensors/um30/um30-213113/p/p222357)

4. The Siemens LOGO! PLC electronic control unit (ECU) (fig. 16), which receives the signal from the position sensor and controls the proportional valve to adjust the cylinder position.

Fig. 16 - Electronic Control Unit (ECU) PLC Siemens LOGO!

(https://www.siemens.com/global/en/products/automation/systems/industrial/plc/logo/logo-basic-modules.html)

5. Additional sensors (optional):

5.1. The WIKA A-10 pressure sensor (fig. 17) is employed to monitor the pressure in the system for the purposes of protection and diagnostics.

Fig. 17 - WIKA A-10 pressure sensor

(https://www.infinitrade-romania.ro/produs/marcicomercializate/wika-instrumente-de-masura/masurarea-presiunii-wika/wika-senzori-de-presiune/senzor-de-presiune-wika-model-a-10/)

5.2. The Danfoss DST P92 flow sensor (see Figure 18) is utilised for the purpose of measuring oil flow, thus facilitating fine adjustments.

Fig. 18 - Danfoss DST P92 flow sensor

(https://www.danfoss.com/en/products/sen/sensors-and-transmitters/industrial-pressure-transmitters/dst-p92s/)

6. Cable and electrical connectors required to connect the sensors and distributor to the control unit.

Operating principle:

- The operator sets the desired depth on the Siemens LOGO! PLC interface.
- The Temposonics MH magnetostrictive cylinder position sensor measures the cylinder position in real time and sends data to the Siemens LOGO! PLC.
- The Siemens LOGO! PLC compares the value measured by the distance sensor with the desired setting and sends a signal to the Danfoss PVG 32 proportional valve.
- The Danfoss PVG 32 proportional hydraulic valve adjusts the oil flow to position the cylinder as commanded.

The automation of the linear electric actuator (Concentric LACT4P-12V-20) for seeding depth control comprises the following components:

1. The Pololu Jrk G2 18v19 Pololu Jrk G2 18v19 actuator controller (fig. 19), which controls the direction and speed of movement. This actuator has an internal potentiometer, which measures the exact position of its stroke and transmits the signal to the controller.

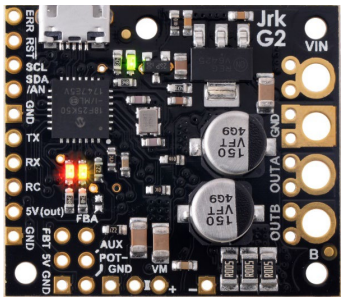


Fig. 19 - Pololu Jrk G2 18v19 actuator controller

(https://www.pololu.com/product-info-merged/3146)

2. Siemens LOGO! PLC control unit (fig.15), which processes the sensor data and controls the actuator.

3. Power supply with motorcycle battery The Exide 12V 12Ah, EB12AL-A2 (fig. 20) Exide 12V 12Ah motorcycle battery (fig. 20), which provides the power for the actuator and controller.

Fig. 20 - Exide 12V 12Ah motorcycle battery, EB12AL-A2

(https://www.baterii-acumulatoare.ro/baterie-exide-moto-12ah-eb12al-a2)

Operating principle:

- Setting the desired depth – The operator enters the value on a control panel or it is predefined in the Siemens LOGO! PLC.
- Actuator position measurement – The internal potentiometer transmits the current position to the ECU.
- Comparing values – The Siemens LOGO! PLC checks whether the current position corresponds to the desired setting.
- Actuator control – If there is a difference, the Siemens LOGO! PLC sends a signal to the actuator controller to extend/retract it.
- Automatic corrections – The system continuously monitors the seeding depth and makes adjustments in real time.

CONCLUSIONS

1. Ensuring a constant planting depth in crops of grass crops such as maize and sunflowers is essential for uniform emergence, whereas an incorrect depth can lead to uneven crop growth. If seeds are placed too close to the surface (below 3 cm), they risk drying out quickly in arid soil. When seeds are placed at the optimum depth (4-6 cm), they benefit from optimal contact with the soil, which ensures rapid and uniform germination. If the seeds are placed too deep (over 7 cm), sprouting is delayed and uneven, as the seeds use more energy to reach the surface.
2. The left-right screw-pull coulter depth adjustment is notable for its simplicity of construction and low cost. However, it is also characterized by a protracted adjustment time and a tendency to err on the side of under-correction with regard to ensuring the correct sowing depth.
3. The hydraulic cylinder seeding depth adjustment offers the advantage of being able to make quick and accurate adjustments directly from the tractor cab; however, there is a risk of oil leakage from the hydraulic circuit.
4. The seed depth adjustment with an electric linear actuator provides precise adjustment with full automation possible, has low power consumption and minimum maintenance, but there is a possible delay in response compared to a hydraulic system.
5. The validation of the design of an automatic seed depth control system (hydraulic cylinder or electric linear actuator) shall be carried out by conducting performance tests to confirm that the seed depth control is effective under varying field conditions. The following tests shall be conducted:
   - checking uniformity of sowing;
   - testing sowing depth on different sowing depths on different fields;
   - measuring impact on sowing quality (uniform plant germination).
6. The utilization of a hydraulic cylinder or electric linear actuator seed depth adjustment system has been demonstrated to be advantageous for a number of individuals and entities within the agricultural sector. These include farmers seeking to enhance the accuracy of their seeding operations, equipment manufacturers developing advanced technologies, machine operators seeking greater control, and agricultural researchers studying seeding efficiency. The integration of this technology has been demonstrated to enhance productivity, reduce financial expenditure and safeguard the environment.

ACKNOWLEDGEMENT

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VIBRATORY CULTIVATORS FOR SUSTAINABLE AGRICULTURE: A REVIEW OF DESIGN, PERFORMANCE, AND SMART TECHNOLOGIES

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CULTIVATOARELE VIBRATOARE ÎN AGRICULTURA SUSTENABILĂ: ANALIZĂ A PROIECTĂRII, PERFORMANȚEI ȘI TEHNOLOGIILOR INTELIGENTE

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Keywords: *Vibratory cultivators, Soil compaction, Energy efficiency, Sustainable agriculture, Precision agriculture*

ABSTRACT

In terms of energy consumption and its effect on the long-term health of the soil, tillage is one of the most demanding farming practices. The usage of vibratory cultivators, which lessen the draft power needed, improve soil breakdown, and can consume less energy overall, has shown promise. When vibration frequencies are appropriately set, field testing have demonstrated certain advantages, including lower clod sizes and less need for traction. Similar research on tractor-rotary tiller systems shows improvements in soil performance as well as the significance of vibration control for the operator's and the machine's safety.Simple vibration has not been the focus of study in recent years. In order to increase efficiency and lessen adhesion issues in wet soils, new systems now employ cameras to assess soil roughness and only activate vibration when necessary. Using nature as inspiration, other research has demonstrated that biomimetic tool designs may reduce resistance by almost 10%. On the digital side, real-time soil compaction estimation has been successfully achieved through the use of machine learning and vibration data.When combined, these developments suggest that vibratory tillage, bio-inspired designs, and smart sensors will be used in the future to improve the sustainability and efficiency of soil management.

REZUMAT

În ceea ce privește consumul de energie și efectele asupra sănătății solului pe termen lung, prelucrarea solului este una dintre cele mai solicitante practici agricole. Utilizarea cultivatoarelor vibratoare, care reduc puterea de tracțiune necesară și îmbunătățesc fragmentarea solului, scăzând consumul total de energie, s-a dovedit promițătoare. Testele din câmp au arătat anumite avantaje atunci când frecvențele vibrațiilor sunt setate corect, inclusiv brazde de pământ mai mici și o nevoie redusă de tracțiune. Cercetări similare privind sistemele tractor–freză rotativă arată atât îmbunătățiri ale performanței solului, cât și importanța controlului vibrațiilor pentru siguranța operatorului și a utilajului.În ultimii ani, vibrațiile simple nu au mai fost în centrul studiilor. Pentru a crește eficiența și a reduce problemele de aderență în solurile umede, sisteme noi folosesc camere pentru a evalua rugozitatea solului și activează vibrația doar atunci când este necesar. Inspirându-se din natură, alte cercetări au demonstrat că uneltele cu design biomimetic pot reduce rezistența la înaintare cu aproape 10%. Pe partea digitală, estimarea în timp real a compactării solului a fost realizată cu succes prin utilizarea datelor vibraționale și a algoritmilor de învățare automată.Luate împreună, aceste progrese sugerează că în viitor lucrările solului cu organe de lucru vibratoare, designurile bio-inspirate și senzorii inteligenți vor fi integrate pentru a crește sustenabilitatea și eficiența gestionării solului.

INTRODUCTION

One of the most important aspects of agricultural productivity is land preparation. The soil in the field can be improved for crop development by land preparation techniques. Tractor traction is necessary for traditional farming equipment like share plows and disc harrows. On the other hand, because of their many useful functions and reduced power load needs, tractor rotational tillage devices have taken over as the primary technique for land preparation. Thus, the study of a rotary tiller's operating performance will contribute to raising crop output and final operation quality *(Gao Y.. et al, 2024)*. Because of the complex

field working environment, agricultural machinery frequently experiences intense vibrations from multisource excitations while in use, which lowers the machinery's dependability and lowers the quality of the job produced.(*Chen, S.R. et al, 2020*)

A revolutionary approach to contemporary farming, precision agriculture (PA) uses sophisticated sensing, data analytics, and decision-support technology to handle the temporal and geographical variability seen in agricultural areas (*Alfred. et al., 2021*). In contrast to contemporary planters, sprayers, and harvesters, tillage equipment has remained less sophisticated in agricultural operations. However, tillage is becoming more widely acknowledged as a crucial area for innovation to include into precision agricultural systems due to the rise of herbicide-resistant weeds, the requirement for residue management, field smoothing, and data-centric farming (*Janbazi Alamdari et al, 2025*).

Soil compaction is becoming a major issue on a global scale. Compaction now affects over 68 million hectares of land globally (*Oldeman, 1992*), and in the ensuing decades, this amount is predicted to rise. Land use and heavy machinery have been highlighted as key causes to compaction, which the European Union has acknowledged as a serious type of soil deterioration (*Jones, 2004*). Compaction is the most common kind of deterioration in Central and Eastern Europe, where high soil loading is the main cause of the widespread degradation *(Van den Akker, 2004).* These issues highlight how critical it is to precisely determine the degree of compaction on commercial agricultural areas and implement mitigation strategies.

By physically loosening the soil, adding organic matter, creating a uniform planting surface, controlling residue, adding herbicide, and fostering root growth, effective tillage enhances soil conditions for seedbed preparation. Additionally, it's essential for controlling soil compaction, which can hinder downward root development, water penetration, crop production, and nutrient uptake (*Nawaz et. al, 2013*). Tillage and herbicide inputs frequently work in opposition to one another in integrated weed management systems because decreasing herbicide use usually necessitates more mechanical intervention, whereas decreasing tillage intensity tends to increase reliance on herbicides to maintain efficient weed control and minimize yield loss (*Mason et. al, 2020*).

In agriculture, interactions between soil and tools often take place at several stages of crop growth, such as tillage, sowing, crop management, and harvesting. In order to accomplish the shearing, upheaval, failure, movement, loosening, overturning, and fracturing of the soil, agricultural soil-engaging tools (ASETs) and soil engage mechanically, usually with a tractor (*Gursoy et. al, 2017*). The energy required for the overall cropping system is mostly derived from the energy utilized in the soil's operational activities.

Biomimetic, experimental, oscillatory, high-pressure-gas splitting (HGS), line element design (LED), and other techniques are among the tillage resistance reduction techniques used by ASETs. Depending on the power supply, the oscillation technique may be divided into two categories: forced and self-oscillation (*Shagoli et. al, 2010*). By adding a vertical movement to the ASET, this technique can lower the horizontal resulting draught force in line with the mechanical qualities of the soil.

The broad definition of biomimetics is bio-inspired design that is adapted or derived from nature (*Pu et.al, 2016*). Designing and producing a variety of tools by imitating diverse animals has advanced quickly in recent years. The use of biomimetic ASETs to reduce tillage resistance is an excellent example of biomimetic approaches in action. This may be achieved through a variety of processes, such as lowering adhesion and friction on the soil (*Ren et. al, 2008*). The moving mechanisms of bionic prototypes, the integration of biomimetic design, the agronomic requirements, and other methods are just a few of the difficulties that still exist in relation to the selection of effective bionic factors, as biomimetic methods are typically restricted to a specific soil status or tool parameter.

MATERIALS AND METHODS

This review was conducted in order to identify, compare, and synthesize recent research on vibratory cultivators, biomimetic design strategies, and smart sensing technologies for sustainable soil management. The methodology followed a structured approach to literature selection and analysis.

The experiment of Esehaghneygi et. al aimed to investigate how a twin bent-share cultivator's field performance was affected by introducing vibrations at various frequencies. Additionally, the effects on the tool draught force and soil parameters of an additional vibratory motion at two frequencies and constant amplitudes are examined. The impact of lowering the draught force required in the event of longitudinal oscillations has been somewhat demonstrated in a prior research; however, the outcome of lowering the traction force in the case of transverse oscillations of a twin bentshare cultivator has not yet been documented. Based on the sideway failure zone reported by, the trials were carried out on a practical scale

using a vibrating dual bent-share cultivator with a 120 mm overlap of soil disturbance reported by *Salar et al. 2013*.(Figure 1).

The two bent-share combinations had identical descriptions. The experimental tools had a shared length of 350 mm (perpendicular to the moving direction), a share width of 110 mm, an attack angle of 15° (the angle of the leading edge), and a bent angle of 10° (the angle of the trailing edge). Because of the tool-tip's location in relation to the pivot point, the oscillation angle for this forward blade twin bent-share cultivator would be quite small. A Ck45 steel plate that was 10 mm thick was used to make the tools' shank and share. The tool oscillated thanks to a crank follower mechanism.

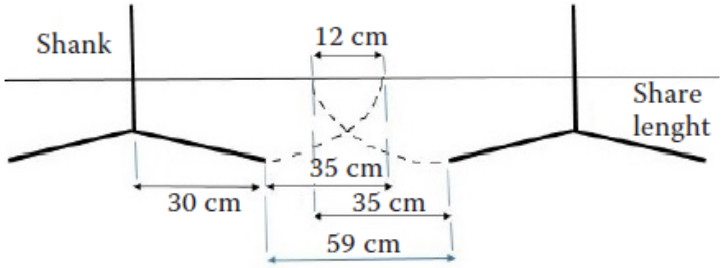

Fig. 1 - The soil failure zone overlap for the vibrating twin bent-share cultivator's tool spacing

Since the motion of the reciprocating tools was therefore perpendicular to that of the tractor, the tools were supported by two slider bearings on an upper pivot (Figure 2).

The field trials were carried out at the Research Farm of Isfahan University of Technology (Iran) using a split-plot factorial design with three replicates. Barley stubble from the previous season was present, and plots (3 m × 50 m) were arranged within randomized blocks. The dual bent-share cultivator was tested in vibrating (0.88 and 2 Hz) and non-vibrating modes, at two depths (100 and 200 mm) and two soil moisture levels (0.7 and 0.9 of PL). Tractor speed was kept constant (0.28 m·s–1) and a control with non-vibration tools was also included. Measurements included draught force, specific draught, disturbed soil cross-sectional area, mean weight diameter (MWD), soil bulk density, cohesion, adhesion, and friction angles. Soil properties such as water content, plastic limit, and texture were determined using standard methods.

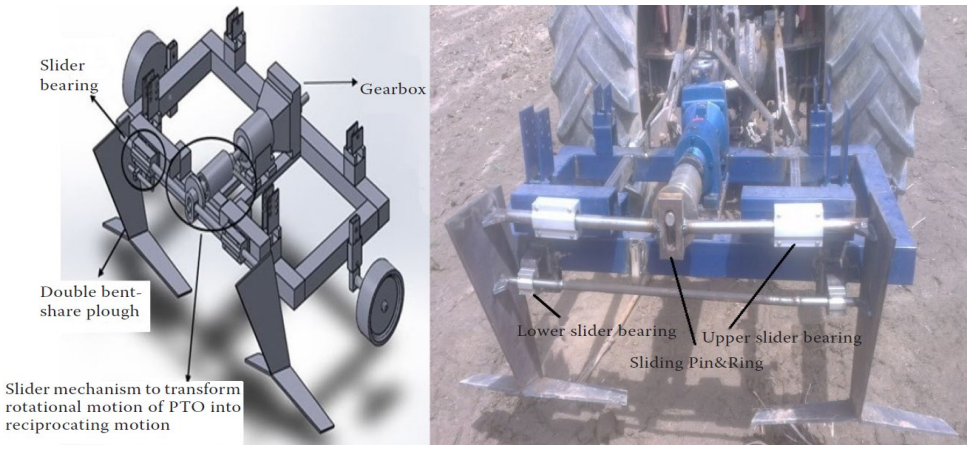

Fig. 2 - Overview of the vibrating dual bent-share cultivator

The study by Gao et al. (2024) proposed a novel methodological framework for analyzing vibrations during tractor–rotary tiller operations. Instead of treating the tractor and tiller separately, the authors investigated the combined interaction of the tractor, the three-point suspension mechanism, and the rotary tiller as a single system (Figure 3). To capture vibration transfer comprehensively, multiple tri-axial acceleration sensors were mounted at key locations, and tests were conducted under real field conditions at forward speeds of 2.1, 3.6, and 4.5 km/h.

The vibration signals were processed in both the time and frequency domains, enabling assessment of acceleration amplitudes, resonance frequencies, and vibration transmission pathways. This approach not only provided insights into how speed influences system dynamics but also revealed structural assembly

issues such as asymmetry in tractor cab vibrations, demonstrating the potential of vibration monitoring as both an operational analysis and diagnostic tool.

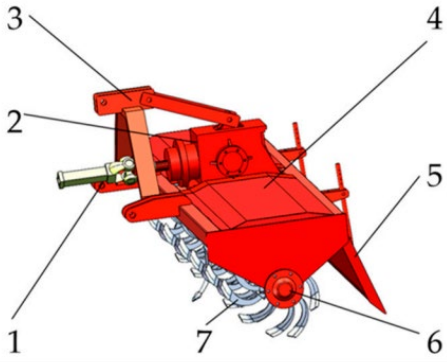

Fig. 3 - Main structure of rotary tiller:
1-Transmission system, 2- Gear box, 3- Linkage frame, 4- Cover,
5- Soil leveling board, 6- Rotary tiller shaft, 7- Rotary tiller blade

Overall, the methodology highlights how integrating multi-point sensor data with dual-domain analysis can uncover both performance-related and structural issues in tractor–tiller systems. This provides a valuable reference for optimizing implement design, reducing vibration-induced resistance, and improving operator comfort. Such an approach expands the role of vibration testing from simple measurement to a comprehensive diagnostic and design-support tool.

The article by Wang et al. (2024) provides a comprehensive methodological synthesis of biomimetic approaches for reducing tillage resistance in agricultural soil-engaging tools (ASETs). Unlike earlier studies that often tested isolated prototypes, this work systematically compared results from 148 paired experiments across 38 studies, quantifying tillage resistance reduction rates (TFRRs) for different tool categories under varying soil conditions.

A key methodological contribution was the identification of three core biomimetic strategies—reducing soil disturbance area, optimizing soil particle movement direction, and improving soil–tool contact conditions—as a framework for evaluating design effectiveness.The review also highlighted the importance of selecting appropriate biological prototypes (e.g., claws, heads, skin textures) based on local soil environments, as well as integrating biomimetic methods with other resistance-reduction techniques such as oscillation

By combining statistical comparisons with design insights, the study advanced a methodology that not only benchmarks past achievements but also guides future tool development toward energy efficiency and sustainability.

For cultivators, biomimetic designs have primarily focused on claw/leg and skin structures inspired by organisms such as mole crickets, dung beetles, and shark skin, with emphasis on reducing soil disturbance and improving contact conditions. Subsoilers, by contrast, have been designed using shanks and cutting shares inspired by bear claws, mole forepaws, and anteater claws, with influencing factors including soil properties, working depth, and soil–tool contact conditions.

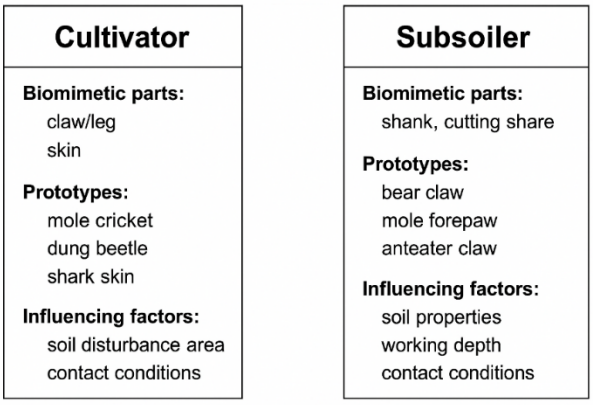

Fig. 4 - Comparative schematic highlighting the biomimetic approaches applied to cultivators and subsoilers

RESULTS

In Esehaghneygi et. al, 2020 study, the draught force was significantly impacted by the working depth. Increasing the working depth from 100 to 200 mm resulted in a 54% increase in the draught force. When the working depth was raised from 300 to 400 mm, the draught force showed the same trend (Guillen-Sanchez et al. 2017). Higher soil surcharge pressure and increased soil-metal friction are the causes of the increase in draught force. Based on the coefficient of determination and the F-values, it seems that the vibration frequency had a greater impact on the draught force than the working depth. The only factor that significantly affected the draught force was the combination of vibration frequency and working depth.

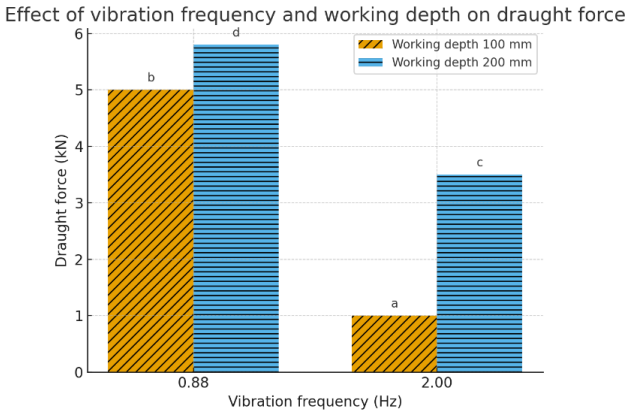

Fig. 5 - Effect of vibration frequency and working depth on the draught force of the vibrating dual bent-share cultivator

(Esehaghneygi et. al, 2020)

According to the study's findings, a twin bentshare cultivator's specific draught and clod MWD are considerably reduced when a vibration at a frequency of 2 Hz is applied. A 1.9 reduction in the draught force and a 13% rise in the soil-disturbed area were the causes of the drop in the specific draught. Because the vibrating cultivator transferred energy to the soil more efficiently, the clod size was less during the soil disturbance process.

The results of Gao et al. 20 study showed that vibration accelerations of the rotary tiller, three-point suspension, and tractor components generally increased with higher forward speeds (2.1, 3.6, and 4.5 km/h), although not uniformly across all frequency bands. The three-point suspension mechanism exhibited the highest vertical acceleration changes (standard deviation 5.914 m/s²), indicating its role as a key transmission path of vibration between the tiller and tractor. Asymmetry in left–right vibration responses suggested possible structural or assembly issues in the tractor. Frequency domain analysis revealed that the rotary tiller resonated around 350 Hz, which could be exploited to reduce soil resistance, whereas the tractor cab resonance at ~280 Hz should be avoided to protect operator comfort and machine durability. At low frequencies (0–80 Hz), cab vibrations remained relatively small, which may be beneficial for driver health. Overall, the study highlighted the dual effect of vibration: moderate excitation can aid tillage efficiency, but excessive transfer to the tractor impairs stability, comfort, and long-term reliability.

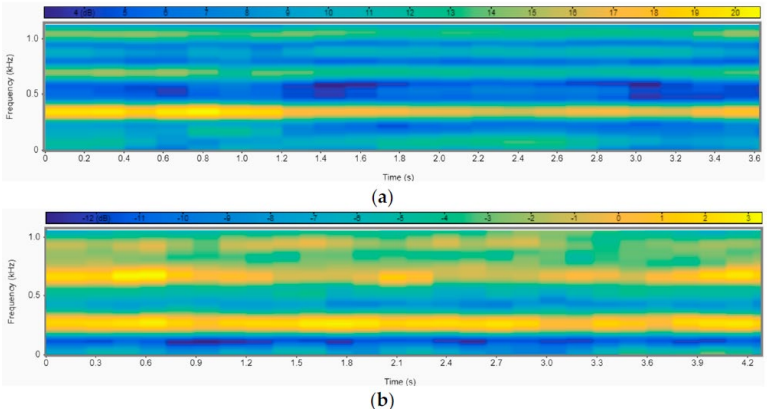

Fig. 6 - Local time−frequency analysis of working condition 1: (a) Gearbox and (b) Cab

In their study, Wang et al. (2024) presented as a result the successful application of shark skin riblet structures to the cutting share of a subsoiler shank, as shown in Figure 7. By mimicking the micro-riblet geometry of the shortfin mako shark (*Isurus oxyrinchus*), characterized by its spacing, height, and angle, the authors demonstrated an effective reduction in soil adhesion and draught force. This biomimetic modification improved soil–tool contact conditions and contributed to enhanced penetration efficiency and lower energy consumption during deep tillage operations.

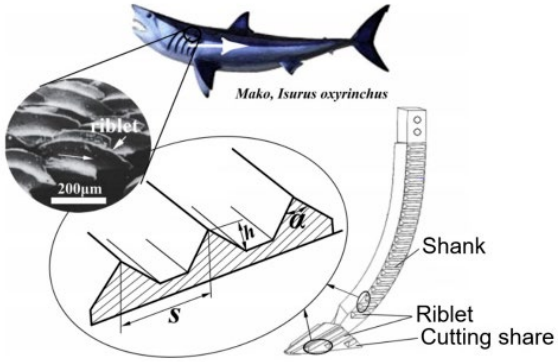

Fig. 7 - Example of a biomimetic design inspired by the skin surface of the shortfin mako shark
(Wang et al., 2024)

The authors also illustrated in Figure 8 how natural structures such as the anteater's claw (8a), the mole's forepaw (8b), the mole cricket's leg (8c) , and the pangolin's claw (8d) can be used as design inspirations for improving soil penetration efficiency.

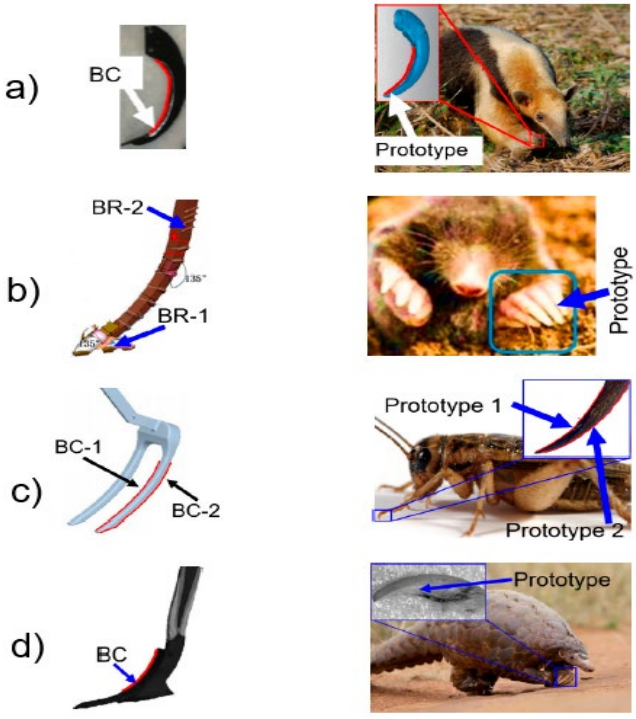

Fig. 8 - Biomimetic parts (BMPs) and their bionic prototypes for subsoiling tools (SSTs)
(Wang et al. 2024)

By translating these biological features into engineered components—such as modified bending radii, claw-like cutting edges, and optimized curvature of the share—subsoiler tools were able to better disrupt compacted soil layers while reducing draught force. These results confirmed that selecting appropriate prototypes from digging and burrowing animals provides a practical pathway for enhancing the performance of deep tillage equipment.

The authors analyzed the factors limiting tool improvement, explained the internal mechanisms by which biomimetic strategies reduce resistance, and summarized performance evaluations across existing

studies. Their conclusions confirmed that biomimetic design provides a promising approach for enhancing the efficiency of ASETs and offers a useful reference for future tool optimization and development.

In their experimental work, Sun et al. (2018**)** applied biomimetic tooth profile (BTP) and biomimetic polygonal convex curve (BPCC) elements to the design of subsoilers.

The authors developed six different configuration modes: a shank with BTP in the normal direction of the shank curve (S-T-N), a shank with BPCC in the normal direction of the shank curve (S-C-N), a shank with BTP in the horizontal direction of motion (S-T-H), a shank with BPCC in the horizontal direction of motion (S-C-H), a tine with BTP parallel to its centerline (T-T), and a tine with BPCC parallel to its centerline (T-C).

These variants provided a comparative basis for assessing how biomimetic modifications influence soil disturbance, draught force, and overall tool performance under subsoiling conditions.

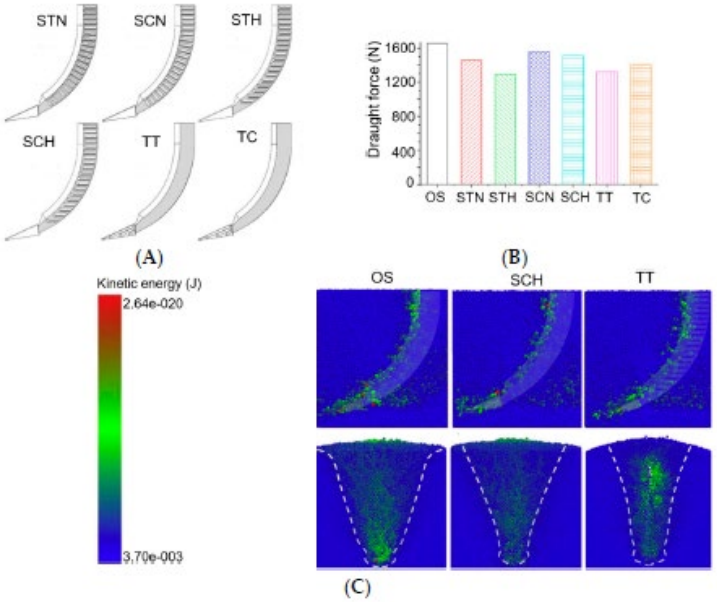

Fig. 9 - Biomimetic subsoiling tool optimization using experimental method: (A) six biomimetic subsoiling tools with various biomimetic riblets, (B) draught forces from various subsoiling tools, and (C) soil disturbance profiles from various subsoiling tools (STN, SCN, STH, SCH, TT, and TC represent six different biomimetic subsoiling tools; OS represents ordinary subsoiling tool)

CONCLUSIONS

Experimental results have shown that applying vibration to cultivators can effectively reduce draught force, decrease clod size, and enlarge the disturbed soil area, demonstrating the advantages of oscillatory tillage. Research on tractor–rotary tiller systems highlights the strong vibration interactions between components, where controlled excitation improves efficiency, while excessive resonance threatens operator comfort and machine durability.

Biomimetic approaches, including riblet-inspired surfaces and claw-like geometries, have proven effective in lowering soil resistance and enhancing penetration efficiency. Further experimental work with biomimetic tooth profiles and convex curves confirmed improvements in subsoiler performance by reducing draught and increasing soil disruption.

Overall, these findings indicate that vibratory mechanisms, bio-inspired designs, and smart technologies represent complementary strategies for reducing energy consumption and supporting sustainable soil management.

ACKNOWLEDGEMENT

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REMEDIATION METHODS OF CONTAMINATED SOILS - REVIEW
/
METODE DE REMEDIERE A SOLURILOR CONTAMINATE - REVIEW

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ABSTRACT

Soil contamination is one of the major global environmental problems, with direct effects on ecosystem quality, agricultural productivity, and human health. The main sources of pollution includes industrial activities, intensive agricultural practices, inadequate waste management and urbanization processes. Pollutants associated with these activities, such as heavy metals, persistent organic compounds, or pesticide residues, can lead to the degradation of the physical, chemical and biological properties of the soil, reducing its functionality. In recent decades, numerous studies have been dedicated to the development and optimization of methods for remediating contaminated soils. They are broadly divided into physical, chemical, and biological methods, each category having specific applicability depending on the type and level of contamination. Conventional ex-situ technologies offer high efficiency but involve considerable costs and energy impact. In contrast, approaches based on biological processes, such as bioremediation and phytoremediation, are increasingly being studied due to their sustainability and compatibility with the principles of the circular economy. This paper aims to highlight the main methods for remediating contaminated soils, the mechanisms by which they work and their effectiveness in different types of contamination. A better understanding of these technologies is essential for promoting sustainable solutions capable of restoring the ecological and economic functions of soils.

REZUMAT

Contaminarea solurilor reprezintă una dintre problemele majore de mediu la nivel global, având efecte directe asupra calității ecosistemelor, productivității agricole și sănătății umane. Sursele principale de poluare includ activități industriale, practici agricole intensive, gestionarea inadecvată a deșeurilor și procesele de urbanizare. Poluanții asociați acestor activități, precum metalele grele, compușii organici persistenți sau reziduurile de pesticide, pot conduce la degradarea proprietăților fizice, chimice și biologice ale solului, reducându-i funcționalitatea. În ultimele decenii, numeroase cercetări au fost dedicate dezvoltării și optimizării metodelor de remediere a solurilor contaminate. Acestea se împart, în linii mari, în metode fizice, chimice și biologice, fiecare categorie având aplicabilitate specifică în funcție de tipul și nivelul contaminării. Tehnologiile convenționale, de tip ex-situ, oferă o eficiență ridicată, însă presupun costuri și impact energetic considerabile. În contrast, abordările bazate pe procese biologice, cum sunt bioremedierea și fitoremedierea, sunt tot mai studiate datorită caracterului sustenabil și a compatibilității cu principiile economiei circulare. Această lucrare își propune să evidențieze principalele metode de remediere a solurilor contaminate, mecanismele prin care acestea acționează și eficiența lor în diferite tipuri de contaminare. O mai bună înțelegere a acestor tehnologii este esențială pentru promovarea unor soluții sustenabile, capabile să redea solurilor funcțiile lor ecologice și economice.

INTRODUCTION

Environmental pollution is one of the most pressing and intensely debated issues globally today. Industrial and urban expansion has led to a significant increase in the degradation of environmental components, manifested in particular by the accumulation of potentially toxic pollutants. Heavy metal

contamination is recognized as a major challenge, with serious implication s for human health and ecosystem balance. In the context of growing demand for a higher standard of living, there is increasing exposure of the population to the harmful effects of environmental pollutants (*Vasilachi, I.C. et al., 2021*). Soil contamination is one of the most persistent and difficult forms of pollution to remedy, caused by the accumulation of hazardous chemicals and imbalances in the natural structure of the soil.

The main sources of pollution include industrial emissions, intensive use of agrochemicals, but also leaching of pollutants from landfills or infiltration of contaminated water (*Santos, M. et al., 2025; Meena, P. M. et al., 2024*). At European level, heavy metals and petroleum hydrocarbons are the most common contaminants, together accounting for almost 60% of all reported cases of soil pollution (*Santos, M. et al., 2025*).

These contaminants include in particular heavy metals such as lead, chromium, arsenic, zinc, cadmium, copper, mercury and nickel, known for their high persistence in soil and low capacity for natural degradation. Their long-term presence has serious implications, affecting human health, ecosystem balance, and food safety. Exposure can occur directly, through contact with contaminated soil, indirectly through the consumption of contaminated food, or through the infiltration of pollutants into groundwater used for consumption or irrigation (*Meena, P. M. et al., 2024*). Industrial activities, such as mining and processing, have consistently been major sources of soil pollution (*Moghimi Dehkordi, M. et al., 2024; Food and Agriculture Organization of the United Nations*).

Fig. 1- Different types of soil pollution

Industrial regions generally have significantly higher concentrations of trace elements and organic pollutants as a result of direct or accidental emissions generated during technological processes. These emissions frequently end up in the soil, nearby surface waters, or the atmosphere, contributing to long-term environmental contamination. Soil also continues to be affected by abandoned industrial sites, persistent historical pollution, and environmentally unmanaged waste disposal sites.

These residual sources remain active factors in contamination (*Food and Agriculture Organization of the United Nations*). The authors of the paper (*Crăciun, A.I. et al., 2024*) highlighted that industrial activities carried out in the past at the former chemical plant in Turda caused soil and water contamination with pesticides and heavy metals, generating persistent risks to the environment and human health. The situation requires continuous monitoring and the implementation of effective remediation strategies to limit the impact

on ecosystems and protect the exposed population. Copșa Mică is another example of extreme industrial pollution, where uncontrolled activities in the metallurgical industry have led to severe contamination of the air, water, and soil with heavy metals and toxic gases, profoundly affecting the health of ecosystems and the local population (*Rotaru A., 2010*). On an urban scale, heavy metal contamination is not limited to industrial areas, but also affects green spaces such as public parks.

The study (*Ene, A. et al., 2024*) shows that factors such as intense traffic, the age of parks, the long-term use of pesticides, as well as urbanization and rehabilitation processes contribute to the progressive accumulation of pollutants in the soil. Thus, soil contamination becomes a systemic problem with a cumulative impact on public health and the quality of the urban environment. The paper (*Onakpa, M. M. et al., 2018*) highlights that high levels of lead concentration in soil can reduce its fertility, while very low levels can negatively affect essential plant processes such as photosynthesis, cell division (mitosis), and water absorption. These imbalances can cause toxicity symptoms, such as darkening of leaves, wilting of mature leaves, reduced foliage development, and the appearance of short, brown roots.

Human activities can cause soil pollution both directly and indirectly. For example, inefficient drainage and increased runoff can contaminate nearby land and waterways. Uncontrolled waste disposal leads to its decomposition in the soil, releasing various chemicals and pollutants. These pollutants can seep into groundwater or be carried into the local water supply. Excessive waste storage also promotes the growth of bacteria in the soil, which, through decomposition processes, generate methane gas, a major contributor to global warming and air quality degradation. In addition, this process produces unpleasant odors and negatively affects quality of life (*Verma A., 2021*).

The use of pesticides, herbicides, and fertilizers in agricultural practices can contribute to the accumulation of toxic chemical compounds in the soil. These compounds often persist in the soil environment, affecting soil quality and reducing its ability to support optimal plant growth (*Crăciun, A.I. et al., 2024*; *Tăbăraşu, A. et al., 2021*).

In addition, the accumulation of toxic substances in plants can have adverse effects on human and animal health. Excessive application of chemical fertilizers contributes to soil acidification and the formation of soil crust, which leads to a decrease in organic matter content and beneficial microorganism activity. These changes in soil pH favor the proliferation of pests and can amplify greenhouse gas emissions (*Das, H. et al., 2023*).

The main sources of hydrocarbon contamination, which include production processes, transport pipeline and refinery failures, as well as tank leaks or accidents, can seriously affect soil quality, disrupting the ecological balance. This contamination negatively affects the structure and functioning of soil ecosystems by destroying beneficial microorganisms and altering the physical and chemical properties of the soil, generating long-lasting effects on the environment (*Crăciun, A.I. et al., 2024*). In fine soils, hydrocarbon contamination can cause significant changes in textural and structural properties, affecting particle size distribution, particle shape, and porosity. These changes lead to a substantial reduction in the number of micropores and specific surface area, while the characteristics of macropores remain relatively constant. In coarse-grained soils, hydrocarbons can adhere to the surface of particles, forming hydrophobic films and clogging both macropores and micropores. Due to the predominance of physical interactions between particles in this type of soil, properties such as texture, porosity, capillary retention capacity (cerosity), and cohesion are significantly affected (*Gonçalves Sales da Silva, I. et al. 2020*). Globally, approximately 8.8 million metric tons of oil are spilled into the aquatic environment each year, with most (approximately 90%) coming from human activities, making petroleum hydrocarbons persistent and dangerous pollutants for the ecosystem (*Ambaye, T. G.et al., 2022*). Soil pollution with oil promotes the transfer of certain oil pollutants to food, causing the biological accumulation and amplification of these toxic substances. This affects not only the nutritional and organoleptic quality of vegetables, but also the integrity of the food chain, generating significant risks to human health and perpetuating a vicious cycle of environmental degradation (*Hu, M., 2020*; *Bouruc, D. et al., 2020*).

Given the major impact of pollution on soil quality, food safety, and public health, there is a growing need to implement effective remediation measures capable of reducing contaminant levels and restoring soil ecosystem functions. Soil remediation is the practice of cleaning contaminated land to reduce the concentration of pollutants to a safe level, prevent their spread, and make the land suitable for agriculture (*https://www.pollutionsolutions-online.com/news/bioremediation/197/breaking-news/what-methods-are-used-for-soil-remediation/58120*). Therefore, in order to reduce exposure risk, restore soil functionality, and ensure ecosystem services, it is essential to implement risk-based remediation strategies aimed at restoring and

recovering contaminated soils for various uses, including agriculture (*Ambaye, T. G. et al., 2022*). The choice of remediation method for a contaminated environment is tailored to each individual site. It takes into account variables such as the nature and composition of the pollutants, the physical, chemical, and biological characteristics of the affected environment, as well as the existing microbial community or the need to supplement it. The selection of the appropriate remediation technique also involves consideration of the mechanisms involved, regulatory requirements, and cost and time constraints (*Ossai, I.C. et al. 2020*).

MATERIALS AND METHODS

The materials for this paper are represented by the review articles, research manuscripts of scientific journals, conference proceedings, scientific books and other online publications and sources of information. All these collected articles were explored, consulted, studied, analyzed and the most important and relevant information was summarized about the impact of soil organic pollutants on the environment. All materials used are cited in the text and presented in the list of references.

RESULTS

Remediation of contaminated areas involves the application of specialized techniques designed to remove or isolate hazardous substances so that the land can be safely reused, in accordance with accepted risk limits for human health and environmental protection. An optimal remediation process should either completely remove contaminants from the soil or reduce their levels below thresholds considered safe, while preventing the spread of pollutants to other adjacent areas (*Bastão de Souza, R. et al., 2013*). In this context, the chapter aims to analyze the techniques used to eliminate or degrade pollutants.

Physical-chemical methods - Physical-chemical treatments play a crucial role in remediating contaminated soils, especially in the case of persistent pollutants such as heavy metals, petroleum hydrocarbons, and pesticides. These methods include a variety of physical, chemical, electrochemical, thermal, and acoustic processes designed to remove, immobilize, or degrade contaminants. The choice of the appropriate method depends on factors such as the nature and concentration of the pollutants, soil properties, site conditions, and specific remediation objectives. In many cases, combining several types of treatments can significantly increase the effectiveness of the intervention (*Coreia, A. A. S. et al., 2025*). Thermal treatment is an effective and frequently used method for remediating oil-contaminated soil, as, depending on operating conditions, a temperature of approximately 600 °C can reduce a concentration of 5,000 ppm below regulatory limits, while for more severe contamination, up to 10,000 ppm, temperatures of up to 900 °C are required to meet the required standards. (*Weng, M.C. et al., 2020*). The use of thermally treated soils in the manufacture of building materials, such as bricks, is an effective solution for both reducing soil contamination and promoting sustainability and efficient use of resources. Although scaling up this method to an industrial level poses challenges related to energy consumption and emissions control, the economic benefits and high potential for soil reuse make it a viable alternative for environmental remediation (*Heidari, S. A., et al., 2025*).

Chemical methods aim to modify the behavior of pollutants by adding substances (amendments or inhibitors) that reduce their solubility in water, limit their diffusion, and decrease their bioavailability in the environment *(Liu, X. et al., 2023).* Soil washing is a remediation method that involves injecting aqueous solutions into contaminated soil in order to dissolve and mobilize pollutants, which are then extracted by pumping. The solutions used are enriched with special additives, such as acids, bases, chelating agents, surfactants, or organic solvents, which facilitate the desorption and transport of contaminants from the soil (*Coreia, A. A. S. et al., 2025*). Based on the data obtained in the study (*Effendi, A.J. et al. 2020*), potassium iodide (KI) proved to be an effective solution for washing mercury-contaminated soil, achieving a removal efficiency of over 88% under optimal conditions (pH = 2, KI concentration = 0.25 M, solid/liquid ratio = 1:15). Following a comparative study on the efficiency of different chelating agents in removing heavy metals from contaminated soil (Table 1), it was found that EDTA (ethylenediaminetetraacetic acid) is the most effective agent, demonstrating a superior solubilization capacity for removing heavy metals, especially lead (*Karthika, N. et al., 2016*).

Another study (*Moutsatsou, A. et al. 2006*) shows that the effectiveness of methods for washing heavy metal-contaminated soils depends significantly on the nature of the metals and the type of extraction agent used, and among the reagents tested, 1 M HCl proved to be the most effective for removing Pb, Zn, Cu, and Mn, but the additional costs generated by the treatment of the resulting acid solutions are a major limitation of this method.

The processes of washing soils contaminated with heavy metals have been extensively studied by the authors of the paper (*Choi, J. et al. 2021*), including through the combined application of conventional mechanical mixing and ultrasound under various operating conditions. The parameters investigated included: HCl solution concentration (0.1; 0.5 and 1.0 M), EDTA concentration (0.01; 0.05, and 0.10 M), liquid:soil ratio (3:1, 5:1, and 10:1), and soil particle size (~4.75 mm; 2.00–4.75 mm; 0.30–2.00 mm, and <0.30 mm).

The results in Figures 2 indicated that the integration of ultrasound with mechanical mixing causes a significant increase in the efficiency of the metal removal process. Furthermore, the use of ultrasound proved to be particularly advantageous under less aggressive washing conditions, characterized by lower concentrations of HCl or EDTA, lower liquid:soil ratios, and smaller soil particles.

Table 1

Comparative Evaluation of Different Agents for Heavy Metal Removal from Contaminated Soils

(Karthika, N. et al., 2016)

Types of metal	Chelating agents	Contamination type	Removal efficiency (%)
Cd Pb Ni Zn Cu	EDTA	Both Artificial and Natural	97-100% 45-100% 24% 54-100% 47-98%
Cd Pb N	HCL	Both Artificial and Natural	98% 94% 55%
Cd Pb Ni	Acetic acid	Artificial	5.2-31.1% 42.2-100% Not exceeds 1%
Cu Ni Zn	Texapon N-40		83.2% 82.8% 86.6%
Cd Zn Cu	Tween 80		85.9% 85.4 % 81.5%
Ni Zn As	Polafix CAPB		79% 83.2% 49.7%
Pb	Citric acid	Artificial	50%

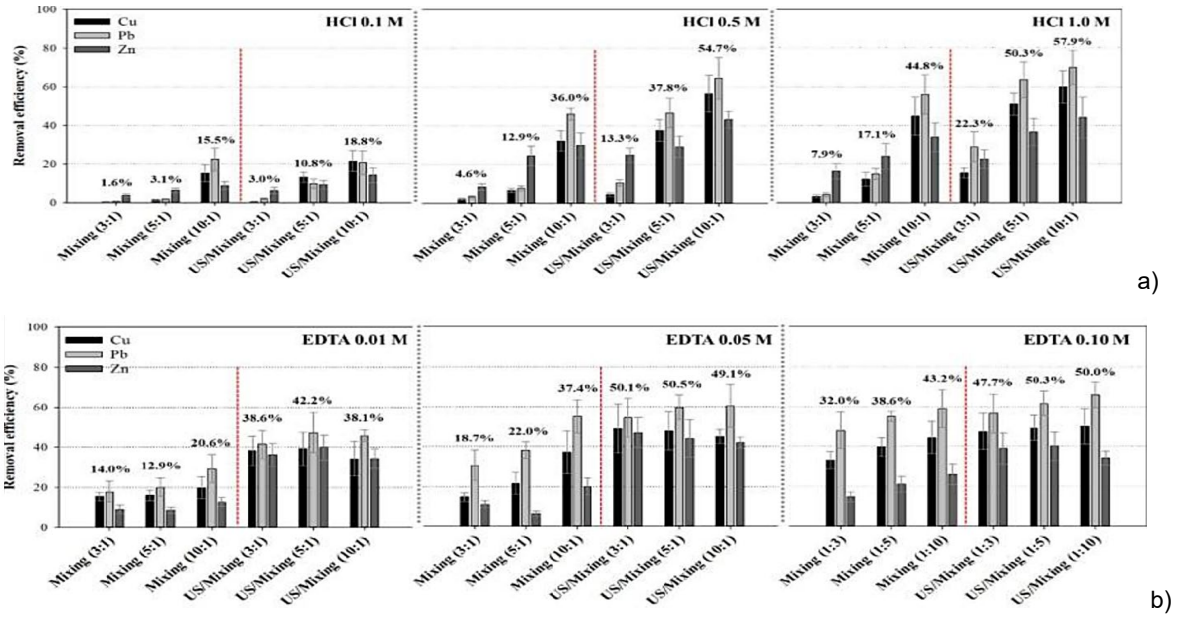

Fig. 2 - Removal efficiency of Cu, Pb, and Zn by mechanical and hybrid (US/Mixing) washing with a) HCl and b) EDTA

(Choi, J. et al. 2021)

Biological methods (Bioremediation) - Bioremediation techniques rely on natural biological processes, such as plants, algae, and microorganisms, capable of effectively degrading a wide range of pollutant compounds, including persistent organic contaminants. By stimulating the growth of microorganisms that use pollutants such as oil, solvents, or pesticides as a source of food and energy, these methods offer a sustainable and effective alternative for remediating contaminated soils. The optimal selection of bioremediation technology, whether in-situ or ex-situ, requires a complex preliminary characterization of the site, including analysis of the type and concentration of contaminants, the physical and chemical properties of the soil, hydrogeological conditions, as well as economic and time-related factors relevant to the implementation of the treatment. (*Gonçalves Sales da Silva, I. et al. 2020*).

Ex-situ bioremediation involves removing contaminated soil for treatment at another location, but it is a complex, risky, and less commonly used method due to logistical difficulties and the risk of spreading contaminants during transport (*Verma A., 2021*).

In situ bioremediation is a biological process carried out directly at the site of contamination and is the preferred method due to the reduction in mechanical operations and the risk of spreading pollutants. The process involves the degradation of organic pollutants by microorganisms, transforming them into inorganic end products such as CO_2, CH_4, H_2O and inorganic salts, under natural or controlled conditions. (*Verma A., 2021*).

In recent years, the use of bacteria capable of degrading hydrocarbons has become a frequently used, effective, and cost-effective method for remediating soil contaminated with petroleum products. Research has shown that various microbial species, such as *Pseudomonas spp.*, *Bacillus spp.*, *Micrococcus spp.*, *Rhodococcus spp.*, *Enterobacter spp.*, *Mycobacterium spp.*, *Modococci spp.* și *Acinetobacter spp.*, have the ability to degrade petroleum compounds. (*Ghoreishi, G. et al., 2017*). Conform (*Qattan S. Y. A., 2025*) *Cupriavidus metallidurans* stands out for its resistance to cadmium and mercury, being able to efficiently break down benzene, which makes it a promising microorganism for the bioremediation of oil sites contaminated with heavy metals. Similarly *Bacillus* strains that produce exopolysaccharides have been shown to be highly effective in adsorbing cadmium and lead from contaminated soils, contributing both to reducing the bioavailability of heavy metals and stimulating plant growth.

The authors of the research (*Nwaehiri, U.L. et al., 2020*) sed two types of treatment containing groups of bacteria to remediate the soil and effluent water from a paper mill. The first type of treatment consisted of *Serratia marcescens, Pseudomonas pyogenes, Erwnia amylovora, Enterobacter cloacae* for the remediation of polluted soi land *Escherichia coli, Acinetobacter baumannii, Erwnia amylovora, Citrobacter freundii for effluent samples, while the second treatment consisted of Bacillus subtilis and Staphylococcus aureus for the contaminated soil samples and Streptococcus pneumoniae for effluent samples.*

The study demonstrated that certain bacteria have the ability to survive in contaminated environments and transform heavy metals into less toxic forms. Although the soil and effluent were not pretreated, the bacteria isolated from the paper mill environment showed a remarkable ability to adsorb toxic heavy metals in a time-dependent manner. Metals such as lead, arsenic, chromium, zinc, and nickel were successfully remediated from the analyzed samples, with treatment 1 showing superior efficiency compared to treatment 2.

Plants used in phytoremediation have the ability to accumulate significant amounts of heavy metals in their root systems, exhibiting tolerance to a wide range of metals and possessing physiological adaptations that allow them to thrive in diverse environmental conditions. Phytoremediation involves several essential mechanisms, including phytoextraction, phytostabilization, phytodegradation, phytovolatilization, and rhizofiltration. These processes are based on the natural metabolic functions of plants, including root absorption, microbial interactions in the rhizosphere, and enzymatic degradation of contaminants (*Ahmad H., 2024*).

The study (*Antoniadis, V. et al. 2021*) concluded that, of the eight plants used in soil remediation research, *Artemisia vulgaris* stood out as the species with the highest heavy metal absorption capacity among the 12 elements analyzed. It was particularly effective in accumulating zinc and cadmium and, to a lesser extent, copper and nickel (Figure 3).

Another study showed that Betula papyrifera can accumulate approximately twice as much copper as most of the other trees analyzed, but only translocates 20% of this element to the foliage, compared to 60% in the case of the other species studied (*https://www.botanyeveryday.com/online-classes/2012-plant-talk-15-plants-for-phytoremediation*).

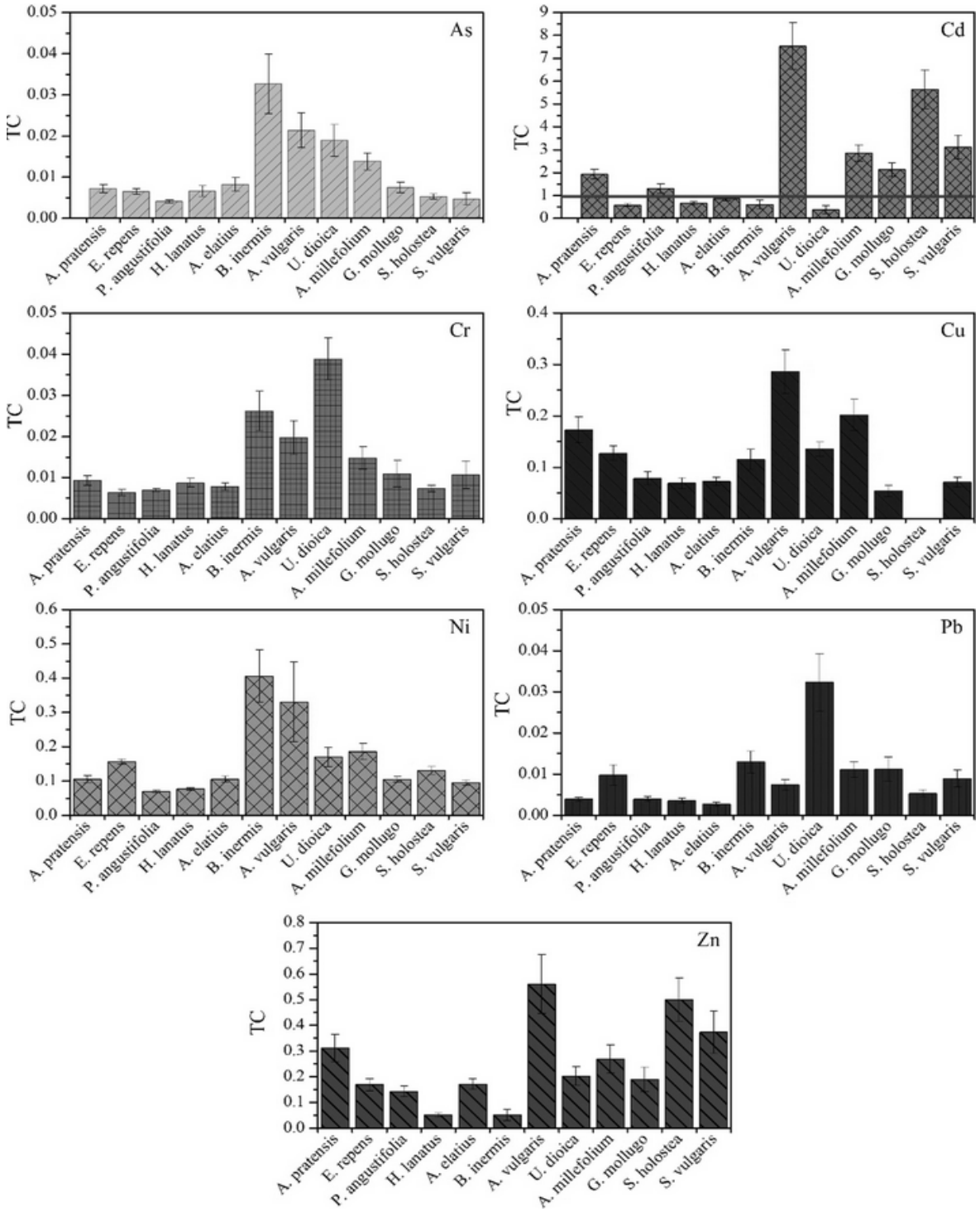

Fig. 3 - The transfer coefficient of potentially toxic elements (As, Cd, Cr, Cu, Ni, Pb and Zn) to the 12 plants
(Antoniadis, V. et al. 2021)

The authors of the study (*Lu., N. et al., 2021*) evaluated the effectiveness of four medicinal plant species, such as *Artemisia capillaris, Taraxacum mongolicum*. *Medicago sativa*, *Plantago asiatica L.* in remediating lead-contaminated soils. The results showed that all four plants contributed to reducing the concentration of lead in the soil, and their effectiveness varied depending on the level of contamination.

Thus, under conditions of slight pollution, the order of effectiveness in removing lead was *Artemisia capillaris*, *Plantago asiatica*, *Medicago sativa* and *Taraxacum mongolicum*. At a level of mild to moderate pollution, the order changed to *Taraxacum mongolicum*, *Medicago sativa*, *Plantago asiatica* and *Artemisia capillaris*. The specific rates of lead removal from the soil were 26.25% for *Artemisia capillaris*, 19.72% for *Plantago asiatica*, 17.71% for *Medicago sativa*, and 13.01% for *Taraxacum mongolicum*.

CONCLUSIONS

Soil pollution remains one of the most complex and persistent environmental problems, with direct implications for ecosystems and human health. A comparative analysis of remediation methods highlights that there is no single, universally applicable solution, but rather a set of technologies that can be adapted to the nature and level of contamination.

Physical-chemical methods, although effective in rapidly reducing pollutants, are often limited by high costs and secondary environmental impacts. In contrast, biological techniques, such as bioremediation and phytoremediation, offer sustainable alternatives with long-term benefits, but require longer application periods and careful monitoring.

The results analysed highlight the importance of combining traditional methods with modern approaches to maximise efficiency and minimise adverse effects. The choice of remediation strategy should be based on a comprehensive site assessment, including soil characteristics, pollutant speciation, economic factors and regulatory requirements.

The development of integrated, low-cost technologies with minimal environmental impact is the main direction for restoring the functionality of contaminated soils and ensuring food security and public health.

ACKNOWLEDGEMENT

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STUDY OF JERK FOR A ROBOTIC ARM
/
STUDIUL DERIVATEI ACCELERAŢIEI PENTRU UN BRAȚ ROBOTIC

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Keywords: *kinematic, 6-axis industrial robot, relative motion*

ABSTRACT
This paper studies the jerk (the derivative of angular acceleration), which is present in the motion of a 6-axis industrial robot used for the manipulation of heavy and elongated shafts. This parameter describes the smoothness of the robot's motion. Higher values of jerk are associated with increased wear of the joints, as well as with vibrations, which lead to reduced motion precision.

REZUMAT
Prezenta lucrare analizează jerk-ul (derivata acceleraţiei unghiulare) ce apare în mişcarea unui robot industrial cu 6 axe destinat manipulării arborilor grei şi alungiţi. Acest parametru caracterizează continuitatea mişcării robotului. Valori ridicate ale jerk-ului sunt corelate cu o uzură accelerată a articulaţiilor, precum şi cu apariţia vibraţiilor, care conduc la diminuarea preciziei de mişcare.

INTRODUCTION

The paper continues the studies presented by the authors in reference *(Lupu and Craifaleanu, 2024)* and focuses on the analysis of the jerk, defined as the time derivative of angular acceleration, in the context of a 6-axis industrial robot designed for the manipulation of heavy and elongated shafts. Jerk is a higher-order kinematic parameter that plays a critical role in describing the smoothness of motion executed by robotic manipulators *(Gasparetto and Zanotto, 2010).* While position, velocity, and acceleration are traditionally considered sufficient to characterize a robot's motion, jerk provides an additional and more refined measure of motion quality. Specifically, it captures the rate of change in acceleration, which directly influences the dynamic stresses experienced by the robot's mechanical structure and drive systems *(Angeles, 2007; Asada and Slotine, 1986; Doroftei and Grosu, 2003; Mihăilă, 2015).*

The importance of jerk minimization becomes evident when considering the practical implications of excessive values of this parameter. High jerk measures abrupt changes in acceleration that generate undesirable mechanical effects, including vibrations in the robot's joints and supporting structures. These vibrations not only compromise the precision of motion and positioning accuracy but also contribute to accelerated wear of components, such as bearings, gears, and actuators. Over time, this leads to reduced operational reliability and increased maintenance requirements. Moreover, in applications involving the manipulation of heavy and elongated shafts, the effects of jerk are amplified, since the payload introduces significant inertial forces. Sudden variations in acceleration can induce oscillations in the load, causing instability and further decreasing the accuracy of the task being performed *(Hogan, 1985).*

Therefore, controlling jerk is a practical necessity in industrial contexts where both productivity and equipment longevity are critical. By minimizing jerk, smoother robot motion, reduced mechanical stress, and higher levels of safety during operation are ensured.

MODEL OF ROBOTIC ARM

Figure 1 illustrates the 3D CAD model of a 6-axis industrial robot, equipped with a custom-designed gripper for handling long and heavy cylindrical shafts. The robot geometry was created using Dassault Systèmes CATIA software and includes six rotational joints. The links and joints are colored distinctly to

improve visualization of the kinematic structure. The end-effector, shown gripping a shaft, consists of two symmetrical jaws, designed to provide secure and balanced clamping along the length of the object.

The model is used for kinematic and dynamic simulations, as well as for trajectory optimization under payload constraints.

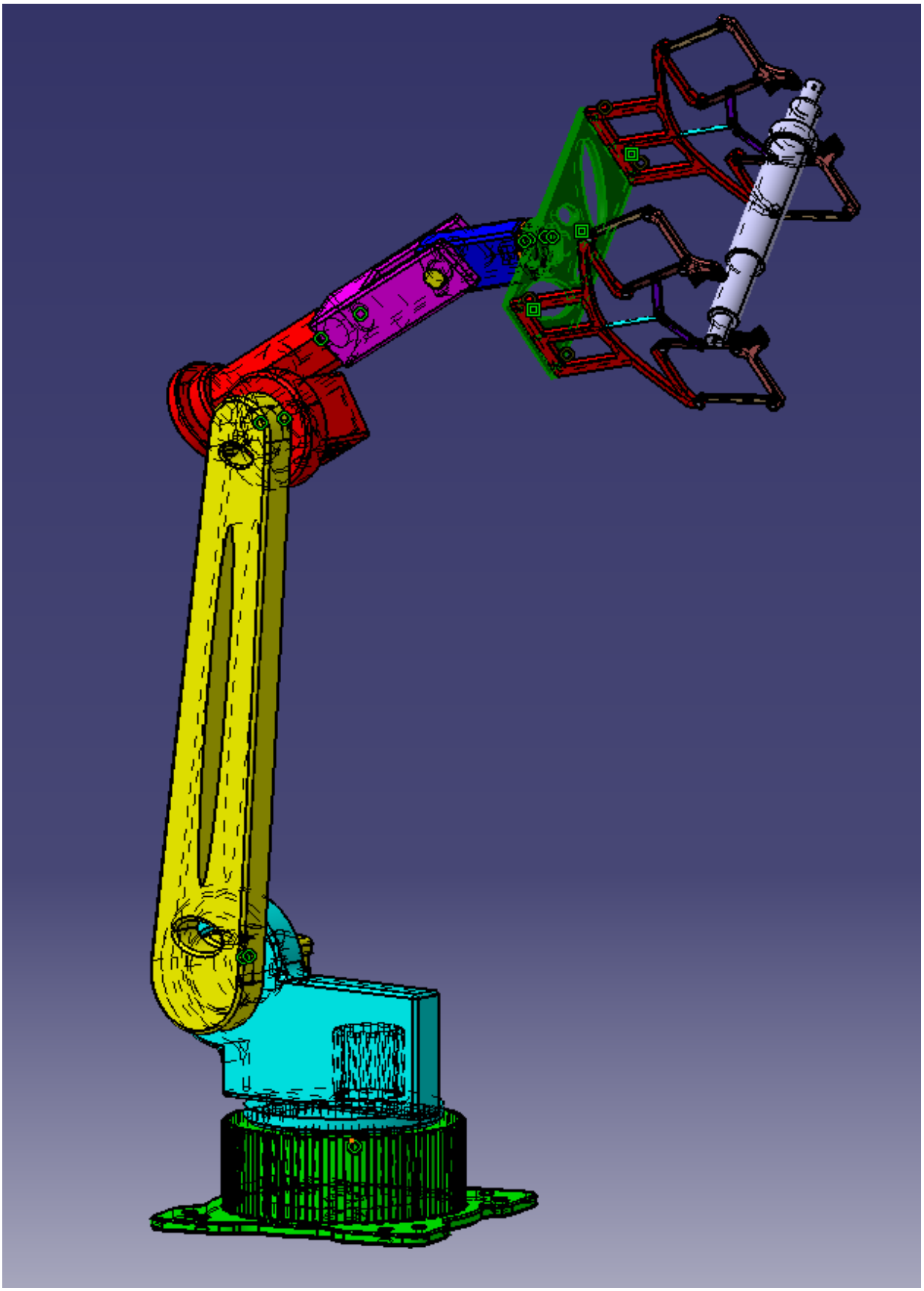

Fig. 1 - 3D model of a 6-axis industrial robot with gripper for long shafts (CAD assembly in CATIA)

Figure 2 presents the kinematic model of the industrial robot manipulator. Each joint and link is represented schematically, with rotational joints denoted by the connecting axes between origin points O_0 to O_7. The rotated coordinate systems $O_ix_iy_iz_i$ (i=1,2,…,7) are displayed in black, while the translated ones, $O_ix'_iy'_iz'_i$, are displayed in red.

The end-effector is not represented, in order to focus on the manipulator structure.

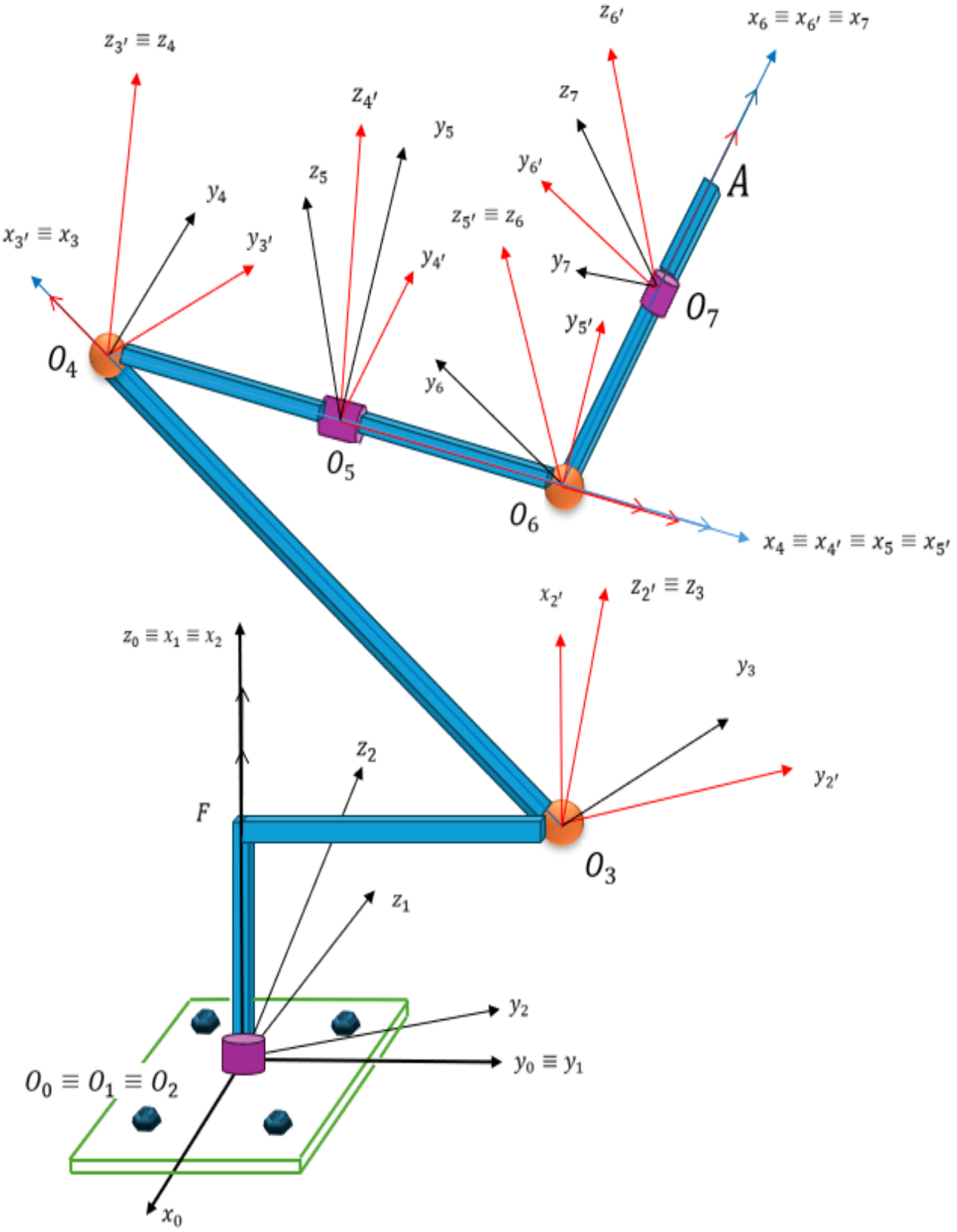

Fig. 2 - Kinematic diagram of a 6-axis industrial robot with reference frames

EQUATIONS OF MOTION

The motion of a robotic arm element is defined by the following law (Fig. 3),

$$q(t)=q_0+\frac{q_1-q_0}{2}\left(1-\cos\pi\frac{t-t_0}{t_1-t_0}\right), \tag{1}$$

where parameter *q* represents the rotation angle of the joint connecting the element to the preceding one.

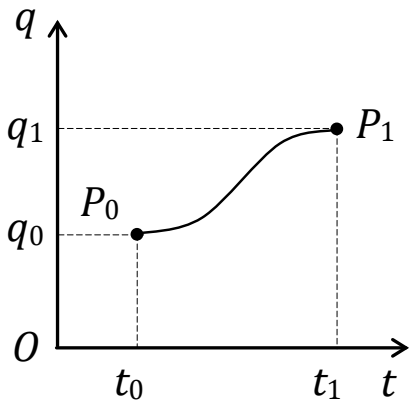

Fig. 3 - Motion law representation of the joint rotation angle

The angular velocity is

$$\dot{q}(t)=\frac{\pi}{2}\frac{q_1-q_0}{t_1-t_0}\sin\pi\frac{t-t_0}{t_1-t_0}, \tag{2}$$

The angular acceleration is

$$\ddot{q}(t)=\frac{\pi^2}{2}\frac{q_1-q_0}{(t_1-t_0)^2}\cos\pi\frac{t-t_0}{t_1-t_0}, \tag{3}$$

The jerk (the derivative of angular acceleration) is

$$\dddot{q}(t)=-\frac{\pi^3}{2}\frac{q_1-q_0}{(t_1-t_0)^3}\sin\pi\frac{t-t_0}{t_1-t_0}, \tag{4}$$

The global effect of the derivative of acceleration, over a time interval [t_0, t_1] is measured by the parameter *(Gasparetto and Zanotto, 2010)*.

$$J=\int_{t_0}^{t_1}\dddot{q}^2(t)\mathrm{d}t. \tag{5}$$

For the law of motion chosen in the present paper, this parameter takes the expression

$$J=\int_{t_0}^{t_1}\frac{\pi^6}{4}\frac{(q_1-q_0)^2}{(t_1-t_0)^6}\sin^2\pi\frac{t-t_0}{t_1-t_0}\mathrm{d}t=\frac{\pi^6}{8}\frac{(q_1-q_0)^2}{(t_1-t_0)^6}\int_0^{t_1}\left(1-\cos2\pi\frac{t-t_0}{t_1-t_0}\right)\mathrm{d}t= \tag{6}$$

$$=\frac{\pi^6}{8}\frac{(q_1-q_0)^2}{(t_1-t_0)^6}\left[t-\frac{t_1-t_0}{2\pi}\sin2\pi\frac{t-t_0}{t_1-t_0}\right]\Bigg|_{t_0}^{t_1}=\frac{\pi^6}{8}\frac{(q_1-q_0)^2}{(t_1-t_0)^5}=120.17\frac{(q_1-q_0)^2}{(t_1-t_0)^5}.$$

NUMERICAL STUDY

A numerical study was performed, considering the values

$$t_0 = 0,$$

$$t_1 = 2\text{s},$$

$$q_0 = 0.2\text{rad},$$

$$q_1 = 0.8\text{rad}.$$

The time variations of parameters (1)-(4) are ploted in Figure 4.

Parameter (6) takes the value

$$J = 1.352\text{rad}^2/\text{s}^3. \tag{7}$$

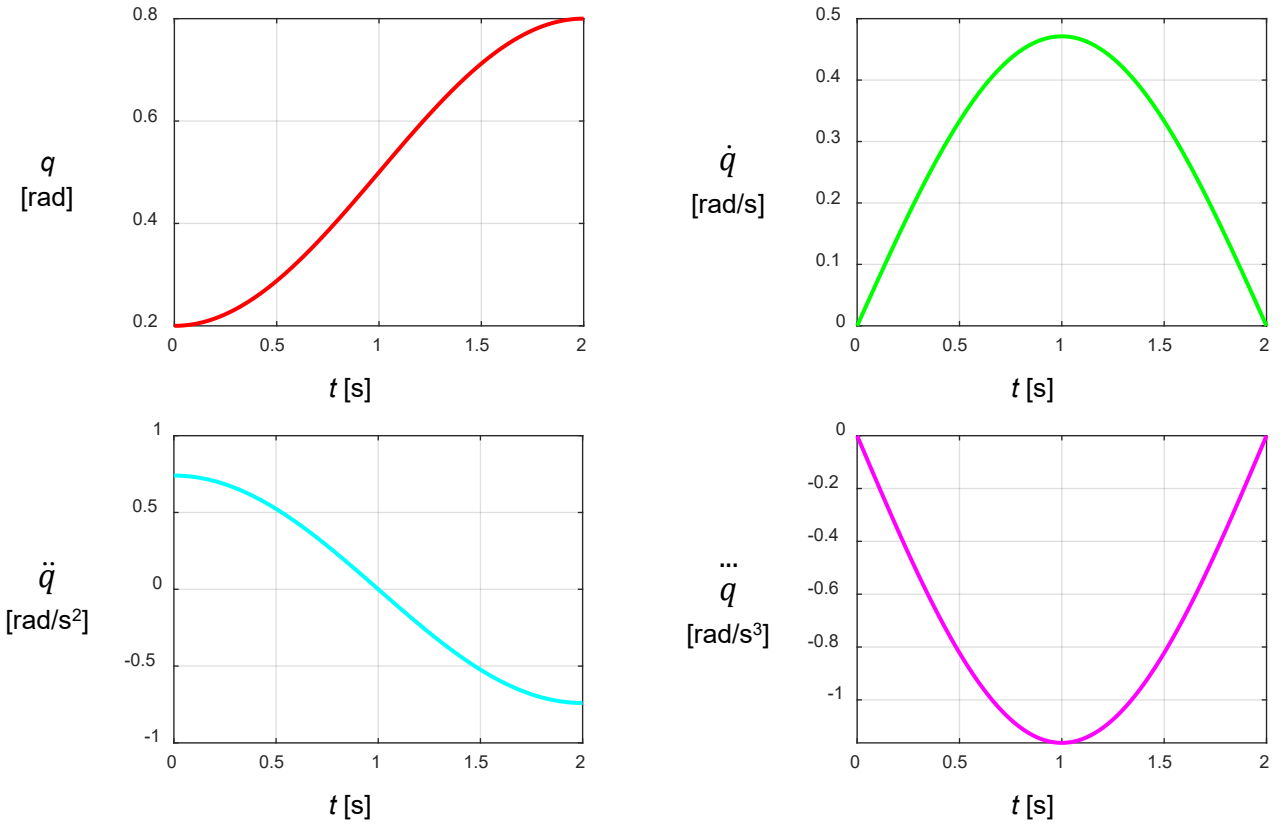

Fig. 4 - Time variation of the rotation angle and of its first three derivatives

CONCLUSIONS

In this paper the jerk (time derivative of angular acceleration) developed in a joint of a 6-axis industrial robot was determined.

A simple sinusoidal law of motion was considered for the rotation angle.

The angular velocity, angular acceleration and jerk were determined analytically.

A parameter J defined as the integral of the jerk squared, calculated on the time interval of the motion, was introduced as a measure of the global jerk effect.

The time variations of the kinematic parameters were plotted as a numerical application.

Future work should be done in order to determine other laws of motion, between the start value q_0 and the final value q_1 which lead to lower values of parameter J.

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THE IMPORTANCE OF PNEUMATIC DEDUSTING SYSTEMS IN CEREAL MILLS
/
IMPORTANȚA SISTEMELOR PNEUMATICE DE DESPRĂFUIRE ÎN MORILE DE CEREALE

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Keywords: *milling industry, grain dust, pneumatic dedusting systems, occupational health, explosion prevention, dust control, industrial safety, sustainable milling, dust emission reduction, process optimization.*

ABSTRACT

In milling units, technological processes such as transport, cleaning, grinding, and sifting of cereals generate significant amounts of organic dust, characterized by heterogeneous composition and variable granulometry. The accumulation of these dust particles poses a critical risk factor, impacting both facility safety and worker health, as well as the quality of the final product. In this context, the implementation of pneumatic dedusting systems represents a fundamental technological requirement, essential for the safe operation of milling facilities. From a theoretical perspective, the analysis of dust formation and dispersion phenomena serves as the foundation for designing and optimizing capture systems. A comprehensive examination of the implications of grain dust highlights the strategic importance of these installations, which are not merely auxiliary technical solutions but integral components with direct effects on occupational health, facility safety, economic efficiency, and environmental protection. By reducing respirable particle concentrations below the thresholds permitted by European and national legislation, pneumatic systems help mitigate medical risks associated with occupational exposure. Furthermore, by eliminating hazardous dust accumulations, these systems minimize the likelihood of deflagrations and explosions, which can have devastating effects on technological installations. From an economic standpoint, the recovery of raw material losses and the reduction of premature equipment wear enhance the overall efficiency of the milling process. The ecological role is equally significant, as these systems limit atmospheric emissions and contribute to sustainable development. Thus, theoretical and experimental research dedicated to improving pneumatic dedusting systems confirms efficiencies exceeding 95% and falls within a multidisciplinary framework, offering substantial applied value for the modernization and sustainability of the milling industry.

REZUMAT

În unitățile de morărit, procesele tehnologice de transport, curățire, măcinare și cernere a cerealelor generează cantități semnificative de praf organic, caracterizat printr-o compoziție eterogenă și o granulometrie variabilă. Acumularea acestor pulberi constituie un factor critic atât din punct de vedere al securității instalațiilor, cât și al sănătății lucrătorilor și al calității produsului finit. În acest context, implementarea unor sisteme pneumatice de desprăfuire reprezintă o cerință tehnologică fundamentală, indispensabilă funcționării în condiții sigure a unităților de morărit. Din perspectivă teoretică, analiza fenomenelor de formare și dispersie a prafului constituie fundamentul pentru dimensionarea și optimizarea sistemelor de captare. Analiza complexă a implicațiilor generate de praful de cereale subliniază caracterul strategic al acestor instalații, care nu reprezintă doar soluții tehnice auxiliare, ci elemente integrative, cu un impact direct asupra sănătății ocupaționale, securității instalațiilor, eficienței economice și protecției mediului. Prin reducerea concentrațiilor de particule respirabile sub pragurile admise de legislația europeană și națională, sistemele pneumatice contribuie la diminuarea riscurilor medicale asociate expunerii profesionale. De asemenea, prin eliminarea acumulărilor periculoase de praf, se minimizează probabilitatea producerii deflagrațiilor și exploziilor, cu efecte devastatoare asupra instalațiilor tehnologice. Din perspectivă economică, recuperarea pierderilor de materie primă și reducerea uzurii premature a utilajelor conduc la creșterea randamentului global al procesului de măcinare. Funcția ecologică este la fel de importantă, întrucât aceste sisteme limitează emisiile atmosferice și contribuie la dezvoltarea durabilă. Astfel, cercetările teoretice și experimentale dedicate perfecționării sistemelor pneumatice de desprăfuire confirmă eficiențe de peste 95% și se înscriu într-un cadru multidisciplinar, cu valoare aplicativă majoră pentru modernizarea și sustenabilitatea industriei de morărit.Praful rezultat în timpul procesării cerealelor este o problemă centrală pentru sănătatea ocupațională, siguranța instalațiilor și sustenabilitatea proceselor industriale. Format din

particule fine, combustibile, praful de cereale poate provoca atât afecțiuni respiratorii, cât și explozii devastatoare dacă nu este controlat eficient.

INTRODUCTION

From a worker health perspective, numerous studies have shown worrying effects. For example, in Nigeria, PM10 levels exceeded 1,000 µg/m³ and PM2.5 above 600 µg/m³, well above WHO limits. Respiratory function tests confirmed a significant decrease in lung capacity in millers (FEV1 = 1.61 L compared to 2.1 L in the control group), concluding that chronic exposure leads to serious respiratory diseases (*Iyogun et al., 2019*).

Fig. 1 - Fire and combustible dust hazard inside a flour processing plant
(https://www.freepik.es/fotos/planta-molino-polvo)

Another study, conducted in Turkey, identified 68 occupational hazards in flour mills, of which 38% were classified as “unacceptable”, the greatest hazards being dust exposure and explosion risk (*Özbakır, O., 2024*). Occupational health and safety in flour mills: A research and risk assessment. International Journal of Agriculture, Environment and Food Sciences). The risk of explosion is equally important. In the United States, around 10 grain dust explosions are recorded annually *(Schoeff, 2006).* The international standard NFPA 61 provides measures for preventing fires and explosions in agricultural and grain processing facilities, including the assessment of potentially explosive areas and the implementation of dust removal and suction systems.In addition, dust has a significant economic and ecological impact.

Raw material losses, accelerated wear of machinery and polluting emissions lead to increased production costs and the carbon footprint of the units. Studies based on Life Cycle Assessment have shown that optimizing technological parameters and reducing emissions through modern technologies can considerably reduce the environmental impact (*Tang et al., 2024; Zhao et al., 2023*).

Recent research in the field of multi-objective optimization suggests that advanced algorithms can simultaneously contribute to reducing carbon emissions, costs and processing times in the industry.In this context, pneumatic dust removal systems are no longer just a technological accessory, but a strategic investment. They help protect workers' health, reduce the likelihood of explosions, improve economic efficiency and support sustainability goals. Through cyclones, bag filters or HEPA systems, dust removal efficiency exceeds 95%, which turns them into the "technological lungs" of milling units, capable of ensuring a safe and clean working environment.Modern pneumatic dust removal technologies include cyclones, bag filters, and HEPA filters, each with specific roles. Cyclones are most commonly used in milling for coarse particle separation, having the advantage of low cost and mechanical strength, but their efficiency decreases for particles smaller than 10 µm. In addition, bag filters achieve efficiencies of over 95% in capturing fine respirable particles, making them essential for maintaining concentrations below explosive and occupational exposure limits (*NFPA, 2017*).For advanced control, especially in critical spaces, HEPA filters are used, capable of retaining over 99.97% of particles with a size of 0.3 µm. By combining these technologies, modern mills can ensure a safe environment for workers and operational continuity.

MATERIALS AND METHODS

Technological innovations

In recent years, research has introduced innovative solutions to complement traditional methods. CFD (Computational Fluid Dynamics) simulations allow modeling of dust flows and pressure distribution in equipment, providing a precise picture of vulnerable points and optimizing the design of installations *(Kurukulasuriya et al., 2020).* In parallel, smart sensors integrated into equipment can monitor dust concentration in real time, triggering alarms or automatic shutdowns when safe values are exceeded. In the field of process optimization, recent research has demonstrated the effectiveness of evolutionary algorithms. One example is the INSDBO (Improved Non-dominated Sorting Dung Beetle Optimization) algorithm, applied

to rectification processes. It reduced carbon emissions by 11.7%, costs by 7.7% and processing time by 6.7%, compared to traditional optimization methods *(Zhang et al., 2023).* Although the study focused on rectification, the methodology has potential for application in optimizing the parameters of dedusting plants, to increase energy efficiency and reduce operating costs.

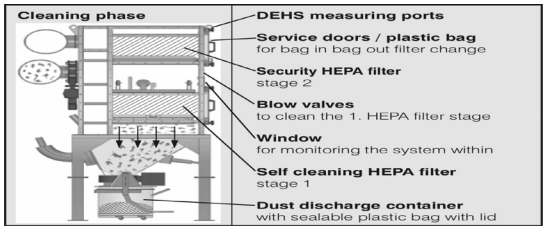

Fig. 2 - Schematic section of a two-stage HEPA filtration system, equipped with cleaning valves, exhaust container and monitoring window

Sustainability and circular economy: Dust recovered from pneumatic systems should not be seen as just a waste, but as a resource. Integrating dust removal into circular economy concepts allows the collected particles to be reused in other production streams, reducing losses and emissions. In addition, reducing energy consumption and carbon footprint is a global priority.

Studies based on Life Cycle Assessment have shown that optimizing process parameters in milling can significantly reduce environmental impact (*Kurukulasuriya et al., 2020*). Therefore, pneumatic dust removal is no longer just a safety measure, but also a tool for sustainable resource management. The work by Solari et al. (2017) constitutes a significant contribution by providing a solid validation of a CFD model applied to air filtration processes in the milling industry. The authors provide detailed experimental data on pressures and velocity distributions inside the pilot plant, which can be subsequently used as benchmarks for similar studies. In addition, the proposed validation methodology – which combines measurements obtained with specialized sensors and numerical simulations performed in ANSYS Fluent – represents a robust framework that can be adapted to other industrial applications where flow phenomena occur through porous media.The 2017 work aimed to develop and validate a CFD numerical model for analyzing the behavior of an air filtration system used in grain mills.

The study was carried out on a pilot plant built within the Industrial Engineering Laboratory of the University of Parma, which reproduces the real conditions in a wheat mill. The analyzed system consisted of a cyclone separator inside which 31 textile filter bags were mounted, a configuration often found in industrial milling units. The methodology involved experimental velocity and pressure measurements using a hot-wire anemometer, a Pilot tube and a differential pressure sensor. These data were compared with the results obtained through CFD simulations in ANSYS Fluent, for different operating conditions. The results showed a very good agreement between the measured and simulated values, both in terms of velocity field distributions and pressure losses.

The validation of the model confirms its applicability as a predictive tool in the design and optimization of dust filtration systems generated by milling processes.Thus, the study demonstrates the potential of using numerical simulation methods in support of the cereal industry, contributing to improving technological performance and reducing dust emissions into the environment. *(Solari, F., Tagliavini, G., Montanari, R., Bottani, E., Malagoli, N., & Armenzoni, M. (2017).*

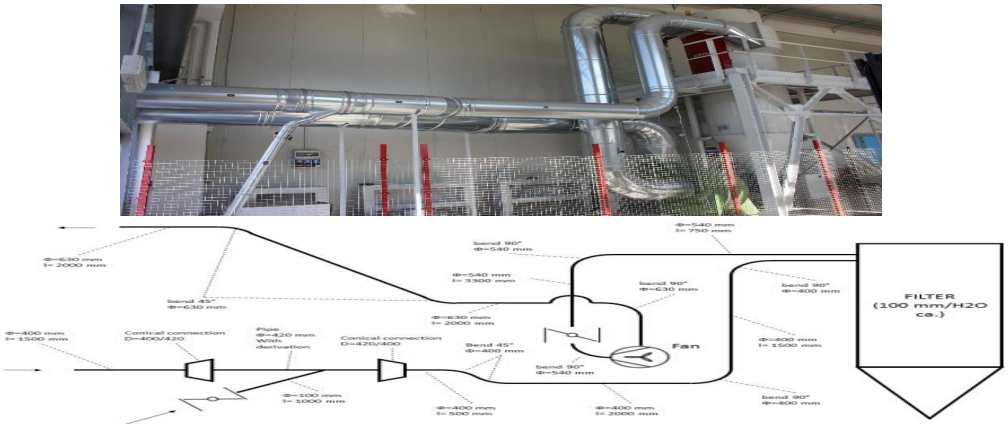

Fig. 3 - Pilot plant used for CFD model validation: (a) photo of the system mounted in the Industrial Engineering laboratory of the University of Parma; (b) technical diagram of the ductwork and bag filter, including the suction fan and the main geometric connections

(after Solari et al., 2017)

The aim of the work was to examine the operation of an air purification system consisting of a cyclone separator and a textile filter equipped with 31 bags. The system was tested in various operating modes to obtain a predictive model useful in the design of industrial facilities. This objective was achieved through CFD simulations, validated through an experimental program carried out on the pilot plant *(Solari, F., Tagliavini, G., Montanari, R., Bottani, E., Malagoli, N. & Armenzoni, M. (2017).*

A first step consisted in the placement and preparation of sensor locations, so that the velocities and pressure differences could be measured both in the filter area and at the inlet and outlet pipes (Figure 2). A hot wire anemometer and a Pitot tube were used to determine the velocities, and the pressure losses were monitored using a differential sensor. In parallel, comparisons were made between the measured air flows and the characteristic curves of the fan, obtained at different inverter frequencies, to confirm the correct operation of the pilot plant *(Solari, F., Tagliavini, G., Montanari, R., Bottani, E., Malagoli, N., & Armenzoni, M. (2017)*. Based on these data, the three-dimensional model of the bag filter was developed, discretized in Ansys MESHING. The computational mesh was designed finely in the narrow areas between the bags, in order to faithfully capture the velocity distribution. CFD simulations were performed in steady-state mode for four inlet velocities: 15 m/s, 19 m/s, 22.5 m/s and 25 m/s *(Solari, F., Tagliavini, G., Montanari, R., Bottani, E., Malagoli, N., & Armenzoni, M. (2017).* The numerical validation consisted of comparing the results obtained by simulation with the experimental measurements. For the velocities in the cyclone volute and in the lower conical part, minimum and maximum values were recorded, subsequently verified by correlation with the numerical curves (*Solari, F., Tagliavini, G., Montanari, R., Bottani, E., Malagoli, N., & Armenzoni, M., 2017*).

RESULTS

The results showed that the CFD predictions fall within the experimental ranges, confirming the correctness of the model from the point of view of the velocity field. Regarding the pressure loss, the values measured with the differential sensor were reported to the inlet velocities determined with the Pitot tube and compared with the simulation results, finding a good agreement from this perspective as well *(Solari, F., Tagliavini, G., Montanari, R., Bottani, E., Malagoli, N., & Armenzoni, M. (2017).*

In conclusion, the study led to the development of a predictive CFD model suitable for the design of air filtration plants in milling. Future research directions include the analysis of the pipe network in terms of velocity distribution and pressure losses, as well as the extension of the model to industrial scale, in order to reproduce real operating conditions *(Solari, F., Tagliavini, G., Montanari, R., Bottani, E., Malagoli, N., & Armenzoni, M. (2017).* The paper by Solari, Lysova and Montanari (2023) describes the development of a digital twin model for the monitoring and predictive maintenance of a cyclone bag filter used in milling plants. The objective of the research was both to detect failures and to estimate the remaining service life of the filter elements. CFD simulations were used to analyze the air flow regimes in various bag clogging states. The results served to identify the optimal position for an additional velocity sensor, intended to complement the differential pressure monitoring, and to define adaptive cleaning procedures with compressed air jets. The integration of experimental and historical data with numerical modeling allowed the construction of the digital twin, connected to the pilot plant through an acquisition system. Validation over a period of one year confirmed its ability to recognize defects such as bag breakage and to provide reliable estimates of the remaining service life.Overall, the study demonstrates that combining CFD simulations with an operational digital twin improves filter efficiency, allows early identification of anomalies, and supports predictive maintenance in wheat mills *(Solari F., Lysova N., Montanari R. (2023).*

The paper highlights several essential contributions:• the possibility of rapid identification of malfunctions, by comparing in real time the measured values with those estimated by the model;• determining the remaining life of the filter elements, an essential aspect in planning maintenance interventions;• optimizing bag cleaning cycles, so as to reduce energy consumption and component wear;• achieving a decrease in operating costs, by avoiding unexpected shutdowns and by using materials efficiently;• ensuring compliance with environmental regulations, by constantly maintaining the emission level below the permitted limits. Through this approach, the filtration system becomes part of an intelligent infrastructure, capable of monitoring its performance, predicting degradation over time, and supporting operational and maintenance decision-making. While the 2017 study focused on the experimental validation of a pilot-scale CFD model, the 2023 research represents a decisive step towards the practical application of digital technologies for predictive management and operational optimization in industrial filtration plants. (*Solari F., Lysova N., Montanari R. 2023*).

Fig. 4 - Integration between the "Physical Twin" (pilot installation equipped with sensors) and the "Digital Twin" (numerical model based on CFD simulations and historical data)

(after Solari, Lysova & Montanari, 2023).

At the bottom, we have the “Physical Twin” – the real pilot plant (cyclone + bag filter) equipped with sensors for real-time data collection. At the top-left, the “Digital Twin” – the numerical model (CFD + historical data + operational data). The information flow is bidirectional: historical and operational data feed the digital model, and the data collected in real time from the physical plant is processed (data logging & data processing). *(Solari F., Lysova N., Montanari R. (2023*).

The processing results allow a series of advanced functionalities:

- evaluation of the degree of clogging of the filter bags.
- detection of anomalies in real time, by comparing the measured values with those estimated by the model.
- analysis of trends to monitor the evolution of the condition of the installation.

Adjustment of the sequence of compressed air jets for cleaning the bags, optimizing energy consumption and reducing wear.Estimation of the remaining life (RUL) of the filter elements, an essential aspect for predictive maintenance. The results obtained show a satisfactory agreement between the CFD simulations and the experimental measurements. The evolutions of the pressure drops, both calculated and experimentally determined, present parallel slopes as the air velocity at the filter inlet changes. The small deviations observed can be associated with the measurement uncertainty generated by the KIMO sensor, positioned near a pipe bend, which influenced the accuracy of the recordings. In case 8, the deviations were more evident, probably due to the fact that the method of simulating clogging by covering with foil does not fully reflect the real situation of a uniformly blocked sleeve. It is worth noting that the differences increase with the intensification of the clogging degree, which explains the more pronounced variation in case 8 compared to case 6. *(Solari F., Lysova N., Montanari R. (2023).* The variation trends of the air velocity at the monitored point inside the filter also confirm the validity of the model, although the deviations are more pronounced.

These differences can be explained by three aspects: (i) the simulations provide only the tangential component of the velocity, while the anemometer captures other components as well, due to constructive limitations; (ii) fixing the sleeves only at the upper part, corroborated with their length of 3 m, allows oscillations that can modify the flow distribution; (iii) the alternation of completely clogged areas with areas unaffected by the foil creates different flow conditions compared to a uniform clogging. (*Solari F., Lysova N., Montanari R. 2023*). Thus, the experimental data confirm the relationships between air flow, pressure drops and velocity at the measuring point, demonstrating that pressure losses increase with the degree of clogging, and the local air velocity intensifies under standardized clogging conditions. However, the model could not be validated regarding the real-time adjustment of the sequence and frequency of compressed air jets (Table 9), since the artificial clogging method used would have compromised the efficiency of the cleaning process. In this regard, future research should aim at testing and validating the model under real industrial conditions, in order to optimally calibrate the cleaning sequence and frequency. (*Solari F., Lysova N., Montanari R., 2023*). The developed digital twin demonstrated the ability to estimate the remaining useful life of the bags (RUL) and identify faults in operation. The model has so far been trained on data corresponding to normal clogging, but its extension to a wider spectrum of operating conditions is necessary to increase its robustness and industrial applicability. In addition, the data generated by the simulations can extend the usefulness of the digital twin by providing information that is difficult to obtain experimentally, such as the distribution of upward velocities inside the bags, the impact velocities on the filter material or the individual flow rate filtered by each element. *(Solari F., Lysova N., Montanari R., 2023*).In 2025, in the paper published in Foods, the characteristics of the materials retained by the bag filtration systems of a wheat mill in southeastern Romania (SC Agro Chirnogi) were analyzed. The study targeted the filters from two technological stages – the cleaning section and the grinding section – by taking samples at the inlet and outlet. The determinations included particle size and distribution (modeled according to the Rosin–Rammler law), apparent and true density, porosity, specific surface area and angle of repose *(Iscru, Voicu G.D., Banu, I. Ungureanu, C., & al. (2025).* The results showed that the particles collected in the grinding section are significantly finer than those in the cleaning section. Although the filters effectively retain the medium and large particle fractions, a considerable part of the very fine particles (PM10 and PM2.5) passes through the filter material. The authors concluded that it is necessary to adjust the technological parameters and implement additional systems for capturing ultrafine particles, in order to reduce emissions and protect the health of operators. (*Iscru, Voicu G. D., Banu, I., Ungureanu, C., & al., 2025*).

CONCLUSIONS

1. Grain dust remains one of the biggest risks in the milling industry. Empirical evidence confirms the effects on workers' health, the vulnerability of plants to explosions and the hidden costs generated by raw material losses and emissions. Modern pneumatic systems – cyclones, bag filters and HEPA – represent the fundamental solution for controlling these risks. Their combination with technological innovations – CFD simulations, smart sensors, evolutionary algorithms – paves the way for a safer, more efficient and environmentally responsible industry. In an integrated vision, dedusting becomes not just a technical requirement, but a strategic investment, indispensable for the sustainable future of the milling sector.
2. Grain dust remains a major risk in milling, but modern dedusting technologies offer efficient and sustainable solutions. - The integration of these systems, in accordance with international standards and supported by applied research, is the key to a safe, efficient and environmentally responsible industry.
3. Textile filters in wheat mills effectively retain medium and large particles, but allow the passage of ultrafine fractions (PM10, PM2.5).
4. CFD validation on pilot plants (2017) demonstrated the accuracy of simulations for flows and pressure losses.
5. The 2023 study introduced the concept of digital twin, useful for fault detection and predictive maintenance.
6. Investigations carried out in Romania (2025) confirm these results and show the need for additional systems for ultrafine particles.
7. The integration of advanced materials, CFD modeling and digital monitoring can increase the efficiency of the filtration process.
8. The implementation of these solutions ensures emission reduction, cost optimization and improved working conditions in the mill.

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TESTING METHODOLOGY FOR A MIXED INTELLIGENT CROP BIRD SCARING SYSTEM

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METODOLOGIE DE TESTARE PENTRU UN SISTEM INTELIGENT MIXT DE SPERIAT PĂSĂRILE DIN CULTURI

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Keywords: *crows, starlings, pigeons, scaring system, acoustic system and light system*

ABSTRACT

This study presents the test methodology for an intelligent mixed system to scare away birds from crops, using modern technologies in the field of precision agriculture. The system consists of distributed components, which can be controlled both locally and centrally, to detect pests early and apply rapid prevention measures. The intelligent mixed protection system uses both acoustic methods (ultrasonic generators and sound emitters at various frequencies and acoustic powers) and light radiation (laser in two colors – red and green – with thousands of patterns and projection intensities). The testing methodology was carried out in the laboratory and in different crops, such as raspberry plantations and apple orchards. The role of the intelligent mixed system developed is to improve crop safety, reduce losses and ensure an effective intervention, with minimal impact on the environment.

REZUMAT

Acest studiu prezinta metodologia de testare pentru un sistem inteligent mixt de speriat pasarile din culturi, folosind tehnologii moderne din domeniul agriculturii de precizie. Sistemul este format din componente distribuite, care pot fi controlate atât local, cât și centralizat, pentru a detecta din timp dăunătorii și a aplica măsuri rapide de prevenire. Sistemul inteligent mixt de protecție utilizeaza atat metode acustice (generatoare de ultrasunete și emițătoare de sunete la frecvențe și puteri acustice variate), cat si radiație luminoasă (laser în două culori – roșu și verde – cu mii de modele și intensități de proiecție). Metodologia de testare s-a realizat in laborator si în culturi diferite, precum plantații de zmeură și livezi de meri. Rolul sistemului intelligent mixt dezvoltat este de a îmbunătăți siguranța culturilor, de a reduce pierderile și de a asigura o intervenție eficientă, cu un impact minim asupra mediului.

INTRODUCTION

Identifying and classifying bird species is a challenge even for ornithologists, due to the high variability in behaviour, morphology, habitat, geographical distribution and adaptability to environmental change (*Gavali et al., 2020; Raj et al., 2020*). The study of bird behavior – such as feeding, reproduction and migration – correlated with habitat changes and specific diseases, is essential for understanding avian ecology. The posture of birds provides valuable information about their behavior (*Lin C.-W., 2022*), But collecting this data involves significant financial resources and efforts.

In this context, modern computer vision technologies based on **deep learning**, especially **convolutional neural networks (CNNs),** have become an important tool in automatic bird recognition, providing outstanding results in numerous studies (*Gavali et al., 2020; Lin et al., 2022*). Unlike sound or video, images are preferred for classification because audio signals can be affected by background noise *(Briggs et al., 2013*).

Frequently used CNN models include:

- **Part-based R-CNN** (*Zhang et al., 2014*) and **Pose Normalized CNN** (*Branson et al., 2014*), which integrate information about bird body parts;
- **D-CNN** (GoogLeNet), used for general classification (*Gavali et al., 2020*);
- **Faster R-CNN,** applied in the automatic detection of bird pests in orchards (*Lee et al., 2018*);

- **YOLO**, specialized in real-time image processing *(Redmon et al., 2016*);
- **HRNet**, which allows the recognition of bird posture by detecting key points (*Lin et al., 2022*);
- Other networks: **CUB-200-2011**, **ImageNet**, **NABirds**, **OverFeat**, as well as specialized sound identification systems such as **BirdNET**.

At the same time, modern machine learning algorithms such as **OpenPose**, **UniPose**, **CPM** and **PifPaf** are used for 2D posture estimation, but their applications to birds are still in the exploratory stage, in the absence of well-defined public datasets (*Lin et al., 2022*).

Therefore, the integration of artificial intelligence in ornithology opens up new perspectives for the efficient and accurate monitoring of avifauna, being of major interest to researchers, farmers and environmental protection institutions.

According to the classification proposed by ***(Micaelo et al., 2023).*** The classic methods of driving away harmful birds from horticultural crops are divided into six main categories:

Visual devices – used to scare birds through visual stimuli, include: scarecrows, reflective strips, kites "hawk's eye" balloons, models of birds, aircraft, drones and flashing lights;

Hearing devices – emit unpleasant or alarming sounds, and include: hunting rifles, pyrotechnic means (pistols and missiles), gas cannons, audio-visual (AV) alarms, predatory bird sounds, high intensity sounds, ultrasound and infrasound;

Chemical deterrents – which affect the behavior of birds or cause them discomfort, such as: tactile repellents, behavioral repellents and the substance methyl anthranilates;

Methods of physical exclusion – which prevent birds from having access to culture, such as: aerial net and foam;

Habitat modification – to make the area less attractive to birds, using: tall grass and application of fungicides;

Active removal methods – which involve capturing or disposing of birds, including: booby traps, live ammunition shooting, falconry (using birds of prey) and surfactants;

Other deterrence techniques – innovative or less used methods, such as: the area of deception, magnets, microwaves and lasers.

Habituation is the most important limiting factor in the effectiveness of classic bird scaring techniques. As they point out (*Pruteanu et al., 2023*), birds can quickly learn that the stimuli used do not pose a real threat. In some cases, these stimuli can even become **conditional clues of the presence of food,** thus attracting birds to the culture and having an effect contrary to the desired one.

To prevent habituation and increase the effectiveness of deterrence methods, it is essential to:

- **the use of a variety of visual** and auditory devices and techniques;
- **activating them as soon as the birds show interest** in the crop, before they form a feeding habit in the area;
- **frequently changing the position and type of devices**, in order to preserve the unpredictability of stimuli.

In addition, **combining different types of control methods** (visual, auditory, chemical, exclusion, habitat modification) have proven to be the most effective strategy in protecting orchards and horticultural crops against harmful birds (*Pruteanu et al., 2023*).

In this context, this paper presents a methodology that has been applied for testing a Mixed Intelligent System for the Protection of Agricultural Crops against pests using acoustic and light rejection elements in order to drive away harmful birds from different crops.

MATERIALS AND METHODS

The Intelligent Mixed Crop Protection System has two different control architectures (acoustic version and acoustic and light version) [11,12] and uses renewable energy sources, digital technologies for pest detection and information processing, acoustic and light repellents for scaring birds.

The system consists of three component modules: power mode, detection mode and rejection mode:

- The power module consists of: solar panels, solar panel system controller, battery and inverter;
- The detection module consists of bird motion detection sensors, smart camera and/or central computer;
- The rejection module consists of various rejection devices, acoustic and light, which work on different principles: sound generator, ultrasonic generator, laser, kites, balloons, reflective tape.

Overview images of the mixed intelligent system for scaring birds from crops in the laboratory (figure 1) and in various crops (figure 2) can be seen below.

Fig. 1 - Experimenting with the system in the laboratory

The intelligent acoustic system in the apple orchard

The intelligent acoustic and light system in raspberry cultivation

Fig. 2 - Experimenting with the system in cultures

1. DESCRIPTION OF THE MIXED INTELLIGENT SYSTEM

1.1. *Hardware components*

*The mixed intelligent system for the protection of agricultural crops (**acoustic version**) is composed of the following physical components:*

◆ **The detection mode** comprises motion sensors (figure 3)

- Sensor Type: PIR
- Operating voltage: 5V – 20V
- Current: 65mA
- TTL digital output: 3.3V/0V
- Adjustable delay: 0.3 sec – 5 min
- Detection range: up to 12 m
- Detection angle: 110°
- Operating temperature: -15°C – +70°C

Fig. 3 - PIR (Passive Infrared) motion sensors

◆ **The rejection mode** comprises sonic generator (figure 4)

- Operating mode: random or sensor-triggered
- Frequency: 3–5 kHz
- Sound power: 105–110 dB at 1 m
- Covered area: approx. 5,000 m²
- Number of speakers: 1
- Power supply: 220V-230V/12V DC
- Dimensions: 15 cm x 22 cm x 10 cm; Weight: 1.4 kg

Fig. 4 - Sound generator for chasing away birds

◆ **Power module** includes: solar panels, solar panel controller, battery, inverter

◆ **Other auxiliary equipment:**

- Holographic tape – for bird-scaring visual reflections
- Kite – imitates the flight of birds of prey for visual discouragement

*The intelligent mixed crop protection system (**acoustic and light version**) is composed of the following physical components:*

◆ **The detection mode comprises the** smart camera (figure 5)

- Type: color, 360° rotation
- Resolution: 1920x1080 pixels (2MP)
- Image sensor: 1/3.7"
- Operating System: Ubuntu Linux
- AI Mode: NVIDIA® Jetson™ Xavier NX
- Digital I/O: 4
- bird detection with YOLOv8 algorithm

Fig. 5 - Smart camera

◆ **The rejection mode** comprises laser system (figure 6) and sound and ultrasonic generator (figure 7):

- Colors: red (650 nm, 100 mW) and green (532 nm, 50 mW)
- Radius Divergence: 60°
- Range: up to 75 m
- Coverage: 10,000 m²
- Classification: Class 3R
- Dimensions: 18.5 x 14.8 x 7.0 cm; Weight: 1.5 kg
- Operating temperatures: -20°C to -40°C

Fig. 6 - Laser system

- Coverage area:
  - Sonic: up to 2–3 ha (30,000 m²)
  - Ultrasonic: up to 400 m²
- Sound pressure: Sonic: 105–110 dB and Ultrasonic: 95–102 dB
- Frequencies: Sonic: 3–5 kHz and Ultrasonic: 15–25 kHz
- Number of speakers: 4 (size 10 x 10 x 15 cm)
- Unit dimensions: 23 x 23 x 13 cm; Weight: 5 kg
- Power supply: 220–240V AC / 12V DC

Fig. 7 - Sound and Ultrasonic Generator

◆ **Power module** includes: solar panels, solar panel controller, battery, inverter

◆ **Other auxiliary equipment:**

- Balloon scarecrows in various colors and drawn with "hawk eyes".

1.2. Detection and reaction algorithms

The acoustic system [11] works in two main operating modes, each governed by a dedicated algorithm:

- **The random mode *(automated via PLC)*** has the following features:
  - controlled by a PLC (programmable logic controller);
  - Activate the sonic generator randomly to prevent birds from getting used to sounds.
  - Interval between activations: 5–30 minutes, with an operating time of 40 seconds.
  - PLC algorithm: uses a pseudo-random number generator to decide the time of the next activation, within the pre-established limits;
  - The advantage of this module is that unpredictably distributed noises increase the efficiency of the system.
- **The Sensor Mode (PIR)** has the following features:
  - PIR sensors detect the movement of birds.
  - Upon detection, the acoustic system is activated instantly, for 40 seconds.
  - It works whenever a movement occurs, as long as there is a natural pause between activations.
  - The sensors are strategically mounted to eliminate blind spots and ensure full coverage.

The change of operating mode is done manually, through a physical selector mounted on the control panel.

The acoustic and lighting system [12] integrates an intelligent algorithm, which combines computer vision with an automatic reaction model based on random logic and adaptivity.

- **Stages of operation:**
  - bird detection through the SMART camera using the YOLOv8 artificial intelligence model, trained for crow recognition;
  - when identifying a bird, the algorithm activates one or both rejection modules (acoustic and light), then a continuous check of the presence of birds is made;
  - if the presence is persistent, the system increases the intensity of the reaction by activating sound/ultrasound and laser, randomly to prevent birds from adapting;
  - the transition between actions (sounds, ultrasounds, laser) is done through a finite state automaton (FSM), which adjusts the response according to the detected behavior.

The YOLOv8 algorithm has algorithmic performance (Precision; Recall; mAP; F1 score: Confidence curve; Confusion Matrix: True Positive; False Negatives).

1.3. Smart functionalities and real-time adaptability

The intelligent acoustic system [11] integrates several functions and adaptation mechanisms to react effectively to dynamic conditions, such as:

- **real-time response** to the presence of birds (through PIR sensors);
- **acoustic adaptability**: the generator can emit various sounds (owl, eagle, heron, etc.) at different frequencies and acoustic pressures;
- **multiple modes of operation** (random or sensor-based) to **prevent birds from adapting;**
- **energy autonomy** thanks to solar panels;
- **modular system**, easy to configure and scalable for larger areas;
- **contribution to Agriculture 4.0**: integrating smart technologies for real-time crop protection, reducing losses and increasing production.

The intelligent acoustic and light system [12] is an advanced implementation of the *Agriculture 4.0 concept*, with intelligent functions that allow automatic adaptation to environmental conditions and adaptable behavior in real time of birds, such as:

- AI Recognition Computer Vision (YOLOv8) for automatic bird detection;
- automatic reaction based on a finite state automaton, which: activates the acoustic, light or combined mode; alternates actions randomly, preventing birds from getting used to it; Variable sounds including distress cries, predatory bird sounds, harassing sounds, configured via toggles (from 1 to 8) for variations;
- continuous monitoring of bird behavior in the protected area;
- automatic adjustment of the intensity and type of reaction;
- continuous evaluation of algorithm performance based on ml metrics (Precision, Recall, mAP, F1);
- immediate response to environmental or behavioral variations;
- solar power, autonomy in areas without electrical infrastructure.

2. METHODOLOGY FOR TESTING INTELLIGENT SYSTEMS FOR DRIVING BIRDS AWAY FROM AGRICULTURAL CROPS

The testing of intelligent acoustic and acoustic and lighting systems had the following objectives:

- evaluation of the functional efficiency of the systems in driving away harmful birds from agricultural crops;
- determination of performance parameters in different environmental conditions (meteorological, soil types, day/night variations);
- checking the adaptability of systems to different types of birds and flight behaviors;
- measuring energy consumption and sustainability of operation based on renewable sources (solar panels and battery);
- identification of technological or site limitations in laboratory and field conditions.

The systems were tested under the following atmospheric conditions, to evaluate the strength and performance of the equipment:

- light / medium / strong wind (0.5 – 15 m/s);
- temperatures ranging from -5°C to +35°C;
- relative humidity: 30 % – 95 %;

- atmospheric pressure: 720 – 780 mmHg;
- Lighting level: sunny / cloudy / dusk day.

The most frequently encountered birds pests in the tested agricultural crops (raspberry crop and apple orchard were monitored), they are shown in the table 1:

Table 1

Bird species monitored

Bird type	Typical behavior	Follow-up reaction
Crow (*Corvus sp.)*	Stationary, repetitive flight	Complete banishment
Common Grass (*Sturnus vulgaris*)	Flock flight, fast movement	Disorientation, dispersion
Pigeon (*Columba livia*)	Stationary, solitary or in pairs	Perimeter avoidance

The measured parameters were: bird scaring efficiency, reaction times and energy consumption.

• **Bird scaring efficiency,** defined as the percentage of birds leaving the protected area at the first activation of the system. Method of visual observation and video recording and calculation, according to the relation (1):

$$Efficiency\ (\%) = \left(\frac{number\ of\ scared\ birds}{total\ number\ of\ birds\ observed}\right) \cdot 100 \quad (1)$$

• **Reaction times,** defined as the time between motion detection and actual system activation. The measuring instruments used were: stopwatch, video camera.

Typical values for the acoustic system of 1.2 – 2.4 seconds and for the acoustic and lighting system of 0.8 – 1.5 seconds.

• **Energy consumption** was estimated by measuring the following parameters: solar energy produced (Wh); energy consumed daily (Wh/day); specific consumption (Wh/m²/day). The measuring instruments used were: network analyzer, digital multimeter, solar controller.

✓ To calculate the solar output of the panel, the relation (2) is used:

E [Wh/day/panel] = P x t .. (2)

where: E is the solar production; - P is the power of the solar panel; - t refers to the hours of sunshine/day.

✓ The relation (3) is for the calculation of energy consumption:

Power [in watts] = Voltage (in volts) x Current (in amps) … (3)

✓ The calculation of the daily electricity consumption for the mixed intelligent system was calculated with the relation (4):

Daily electricity consumption = rated power x average daily usage time …….(4)

✓ the calculation of the kWh consumption, for the mixed intelligent system, was made with the relation (5):

kWh = (rated power in watts x hours of use) / 1000 …….(5)

✓ the specific consumption refers to the energy required to protect a given area, expressed in Wh/m²/day, the calculation relationship (6) is as follows:

$$Specific\ energy\ consumption\ [Wh/m^2/day] = \frac{Daily\ electrical\ energy\ required\ [Wh]}{Protected\ area\ [m^2]} \quad . (6)$$

▪ **Laboratory testing** to verify components under controlled conditions. The aspects analyzed were: functional tests in vacuum (sound, light, power); standardized acoustic measurements (according to SR EN ISO 3744:2011); sensor accuracy and AI validation (YOLOv8) on simulated images.

▪ **Field testing,** in real conditions of use, respectively raspberry crop and apple orchard. The aspects analyzed were: the actual sound/light coverage; birds' response to stimuli; the durability of the system in various weather conditions; energy reliability depending on solar radiation.

The limitations observed during testing are shown in table 2:

Table 2

Limitations observed for the Acoustic System and the Acoustic and Lighting System

Limitation observed	Affected system	Proposed measures
Low noise in strong winds	Acoustic system	Additional sound insulation
Interfering solar reflections with PIR sensors	Acoustic system	Sensor repositioning
Partially shaded solar panel	Acoustic system Acoustic and light system	Position/Tilt Adjustment
Adaptive behavior of birds	Acoustic system Acoustic and light system	Alternating modes

RESULTS

Table 3 shows a structuring of the comparative results between the acoustic system and the acoustic and lighting system, obtained from testing in laboratory and field conditions, with a focus on efficiency, reaction times, coverage, energy consumption and limitations.

Table 3

Results of the tested systems

Parameter	Acoustic system	Acoustic and light system	Observations
Scare efficiency (average)	78–85%	**88–94%**	More effective by combining multiple stimuli
Average reaction time	1.5 – 2.4 seconds	**0.8 – 1.5 seconds**	Light has faster triggering
Efficient covered surface	6000 m²	**6500–7000 m²**	Acoustic-luminous has higher dispersion
Daily energy consumption (average)	120 – 150 Wh/day	**180 – 220 Wh/day**	Grows with LED lighting
Specific energy consumption	0.020 – 0.025 Wh/m²/day	**0.027 – 0.032 Wh/m²/day**	Both in the sustainable area
Bird behavior after 7 days	Observed adaptation trend	**Visible fit reduction**	Light alternation reduces habituation
Reliability in strong wind conditions	Stable, but sound can be attenuated	**More stable, light penetrates visually**	Acoustic and light advantage
Night detection	Limited (PIR sensor and sound)	**Efficient (PIR & Radar & Light)**	Radar and LED increase accuracy
Impact on non-target fauna	Low, but sometimes disturbing to animals	**Minimum (Precisely Directed Light)**	Fine-tuning possible
Estimated cost of implementation	Lower cost	**Higher cost**	Justified cost of superior performance

The comparative testing of the acoustic system and the acoustic and lighting system for the protection of agricultural crops highlighted the fact that:

- The acoustic and lighting system offers superior efficiency in repelling harmful birds, especially due to the combination of visual and sound stimuli, which significantly reduces the birds' adaptation to the system.
- The shorter reaction time and the ability for automatic operation based on detection (PIR, radar and AI analysis with smart camera) allow for rapid and adaptive intervention, improving crop protection.
- The simple acoustic system remains a viable option for small or medium-sized farms, having a lower cost and lower energy consumption, but with limited efficiency in the face of birds that develop tolerance over time.
- Both systems can be integrated into Agriculture 4.0 strategies, with the advantage of renewable power (solar panels), automatic adaptation to field conditions and constant monitoring of wildlife.

The results obtained provide valuable information about how harmful birds react to stimuli and about the efficiency of the system in repelling them, under various agricultural conditions.

CONCLUSIONS

The implementation of mixed intelligent systems, both in acoustic and acoustic and light versions, contributes significantly to the modernization and efficiency of precision agriculture practices, in accordance with the principles of Agriculture 4.0. These systems offer efficient, sustainable and adaptable solutions to combat the presence of bird pests in fruit and shrub crops, reducing production losses and minimizing the use of invasive or polluting methods.

The acoustic model is based on PIR sensors and simple random or reactive triggering algorithms, being effective in areas where rapid detection and audible response are sufficient. It is ideal for orchard applications, offering a good cost-efficiency ratio. On the other hand, the acoustic and light model integrates advanced computer vision technologies (YOLOv8) and real-time analysis, along with multisensory reactions (laser and sound/ultrasound). This approach provides increased automation, adaptability and precision, making it suitable for more sensitive crops (such as raspberries) or areas with high bird pressure.

Both models demonstrate the usefulness of combining smart hardware, adaptive algorithms and renewable energy sources, outlining a clear direction towards sustainable, digitized and ecological

agriculture. The acoustic and humid system is superior in terms of efficiency, reaction speed and territorial coverage, with a moderately increased energy consumption. The simple acoustic system is effective in basic conditions, with low consumption, but risks becoming less efficient over time, due to the adaptation of the birds.

The alternative or combined use of the two models can provide an optimal strategy in large farms or with significant seasonal variations in birds. The work thus supports the smart use of resources and the promotion of sustainable and competitive agriculture.

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EVALUATION OF THE NUTRITIONAL COMPOSITION OF HEMP-BASED DIETARY SUPPLEMENTS AND FUTURE TRENDS

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EVALUAREA COMPOZIȚIEI NUTRIȚIONALE A SUPLIMENTELOR ALIMENTARE PE BAZĂ DE CÂNEPĂ ȘI TENDINȚELE VIITOARE

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ABSTRACT

Current trends in promoting a healthier lifestyle have led to an increase in the consumption of clean, (organic) foods and nutrient-rich food supplements. Medicinal plants are the oldest and most widespread form of medicine in the world and are still used today. In recent years, traditional medicine has received increased attention, demonstrating the potential to obtain products with real benefits for human health, in the context of a more sustainable future. Hemp (Cannabis sativa L.) is among the oldest medicinal plants in human history, recognized for its ability to treat various conditions (cardiovascular, neurodegenerative). Hemp extracts, such as cannabidiol (CBD), are currently used as food supplements due to its properties in relieving pain, anxiety, insomnia. This paper describes an overview of the nutritional content of food supplements containing hemp extracts and future trends in optimizing the utilization of the plant.

REZUMAT

Tendintele actuale de promovare a unui stil de viata cat mai sanatos au determinat o crestere a consumului de alimente curate, (bio) precum si a suplimentelor alimentare bogate in nutrienti. Plantele medicinale constituie cea mai veche și mai răspândită formă de medicină din lume fiind utilizata si in prezent. In ultimii ani, medicina traditională s-a bucurat de o atentie crescuta, demonstrand potentialul in obtinerea unor produse cu reale beneficii pentru sanatatea umana, in contextul unui viitor mai sustenabil. Canepa (Cannabis sativa L.) se numara printre cele mai vechi plante medicinale din istoria omenirii, recunoscuta pentru capacitatea sa de a trata diverse afectiuni (cardiovasculare, neurodegenerative). Extractele de cânepă, cum ar fi canabidiolul (CBD), sunt utilizate în prezent ca suplimente alimentare datorita proprietatilor sale in ameloirarea durerii, anxietatii, insomniei. Prezenta lucrare descrie o imagine de ansamblu a continutul nutritional al suplimentelor alimentare ce contin extracte de canepă si tendintele viitoare in optimizarea valorificarii plantei.

INTRODUCTION

It is estimated that 80% of the world's population regularly uses traditional medicine to treat and/or prevent a variety of diseases *(Oyebode, O. et al., 2016).* Cannabis sativa is among the oldest medicinal plants in human history. In the past, even doctors used hemp to relieve various conditions, including pain. The understanding of the complex chemistry of cannabis has had a favorable evolution along with its multiple therapeutic properties *(Liktor-Busa, E. et al., 2025).*

For example, in traditional Chinese medicine, inflorescences have been used for various health problems such as severe pain, insomnia, cough or shortness of breath, and wounds. The leaves have been recommended for treatments in cases of malaria, respiratory distress, roundworm infections, scorpion stings, hair loss and hair whitening. The bark of the strain has been used for therapeutic purposes for body injuries, and the roots against problems related to spots, difficult births, placenta retention, and bodily injury *(Jin, D. et al., 2020)*.

Even though in previous centuries, hemp was mainly used for textiles, and seeds were considered waste, today, due to their exceptional nutritional qualities and versatility, hemp seeds are used in the food

industry, to obtain oils rich in essential fatty acids, proteins with a high biological value and derivatives for fortification, supplementation and nutraceutical purposes *(Miller, A. et al., 2025).*

To establish a connection between traditional and modern evidence-based medicine, it is essential to identify active biochemical compounds, and their molecular mechanisms must be determined through preclinical and clinical studies. Cannabis is presented with a content of several classes of secondary metabolites, including 14 cannabinoids, 47 terpenoids, 3 sterols, and 7 flavonoids, which are found in the flowers, leaves, bark of the stem, and the roots of the plant.

The identification of bioactive substances, followed by well-structured clinical trials, could turn every part of the cannabis plant into a treatment based on scientific evidence *(Jin, D. et al., 2020).* Currently, the marketing of CBD-based dietary supplements, which is the subject of intense debate in the scientific community, is regulated differently in the United States, Europe and the rest of the world *(Cerino, P. et al., 2020).*

Hemp seeds contain THC (tetrahydrocannabinol) or CBD (cannabidiol), molecules responsible for the psychoactive and therapeutic properties of cannabis. These low levels of terpenophenols make it more suitable for use in food. Certain biological activities of phytochemical compounds (mainly polyphenols and terpenoids) present in hemp seeds confer antioxidant, antimicrobial, and anti-inflammatory properties *(Montero, L. et al., 2023)*.

The health benefits of hemp seed oil are mainly attributed to its desirable ratio of n-3 and n-6, 3:1 fatty acids, which is suggested to be optimal for human nutrition. Unbalanced intake of n-3 and n-6 fatty acids has been shown to be associated with many diseases, e.g., diabetes, cardiovascular disease, and cancer *(Mikulcová, V. et al., 2017).*

MATERIALS AND METHODS

Throughout history, cannabis has been indicated for a wide range of conditions related to pain, inflammation, and mental illness *(Jin, D. et al., 2020).*

The growing demand for high-quality healthy foods and dietary supplements with potential in treating various conditions has led to the development of the hemp products market, figure 1 *(Aloo, S.O. et al., 2022).*

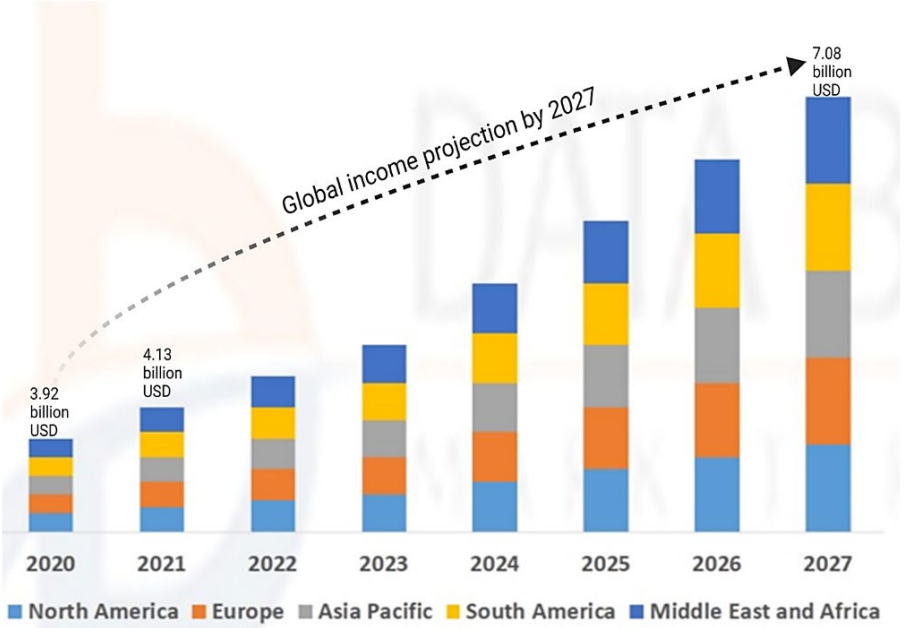

Fig. 1 - Global Hemp Food Market Share, by Regions, Trend, and Revenue Forecast to 2027
(Aloo, S.O. et al., 2022)

The characteristics that make hemp or hemp-derived products suitable for food applications are: solubility (one of the essential properties in determining the potential for incorporation of ingredients into food is their solubility), film formation, emulsification, surface hydrophobicity, nutritional value and bioactive components of hemp seeds (being the only constituent of hemp that can be used as food, hemp seeds have been shown to have great nutritional value). They contain proteins, essential amino acids, carbohydrates *(Aloo, S.O. et al., 2022)*.

Recently published studies, using an optimized method for the chemical characterization of hemp,

identified 189 lipids, including 52 phospholipids and 80 sulfolipids, and 147 compounds belonging to the classes of flavonoids, proanthocyanidins and phenolic acids *(Cerino, P. et al., 2020).* According to the results presented in the literature, hemp terpenes have antidepressant, anti-inflammatory and anxiolytic effects. They participate in photosynthesis and have a protective role in plants *(Salami, S.A. et al., 2020).*

Obtaining phytocannabinoids, which are linked to a variety of medicinal and therapeutic properties with no mentioned adverse effects, is a topic of great interest. The proportion of phytotrope Δ9-tetrahydrocannabinol (THC) remains below 0.2% in industrial hemp varieties, which allows them to be grown legally in many European Union member states.

Harvesting and processing hemp for fiber or seed produces a lot of waste that contains a significant amount of bioactive compounds, such as cannabidiol (CBD), which are the main cannabinoids, along with cannabidiolic acid (CBDA), cannabinol (CBN), cannabigerol (CBG), and cannabichromene (CBC). That is why it is essential to optimize the process of extracting cannabinoids from the residues resulting from the processing of industrial hemp.

Numerous studies demonstrate the beneficial medicinal and therapeutic properties of these non-psychotropic compounds. CBD and CBDA have demonstrated modulating effects on the human endocannabinoid system, possessing analgesic, antibacterial, antidiabetic, antiemetic, antiepileptic, anti-inflammatory, antiproliferative, and antipsychotic properties *(Vági, E. et al., 2019)*.

RESULTS

It is worth noting that numerous cannabinoids, including Δ9 - THC, show their physiological and pharmacological effects via the natural cannabinoid system (endocannabinoid), figure 2 *(Binding, C.A. et al., 2022).*

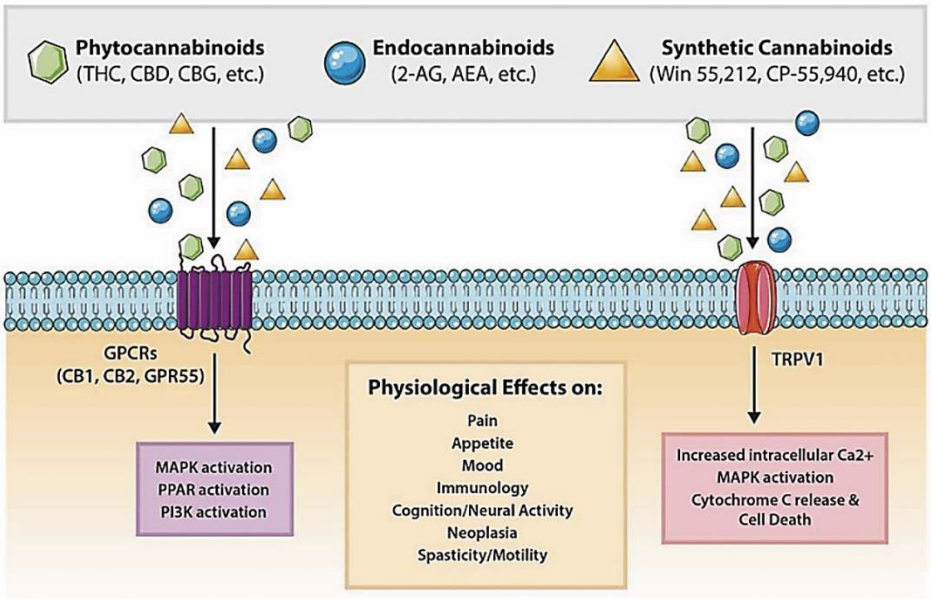

Fig. 2 - Signaling pathways and effects of cannabinoids. Regardless of the type of cannabinoid ligand (phytocannabinoid, endocannabinoid, or synthetic), these compounds mainly interact with GPCR proteins, such as CB1 and CB2 receptors, and GPR55, or with TRP, such as TRPV1, to induce a cellular response. Activated pathways vary depending on receptor activation and have physiological effects on pain, appetite, mood, and many other effects in the body

(Ligare, C.A. et al., 2022)

In addition to endocannabinoids, there are two other sources of cannabinoids, namely phytocannabinoids (produced by plants in the genus Cannabis) and synthetic cannabinoids (lab-generated compounds that can interact with cannabinoid receptors). In the literature there are a number of observations that assess the endocannabinoid system (ligands and receptors), as well as the phytocannabinoids in Cannabis sp. Thus, attention has been directed to medical conditions, disorders and diseases for which cannabis has potential for therapeutic use. In addition, enzymes responsible for breaking down endocannabinoids, such as fatty acid amide hydrolase (FAAH) and monoacylglycerol lipase (MAGL), are also key targets in creating new treatments *(Ligare, C.A. et al., 2022).*

A disproportionate consumption of n-3 and n-6 fatty acids has been shown to be associated with various health problems, including diabetes, cardiovascular disease, and cancer. As a result, aware of the antioxidant and anti-inflammatory effects of hemp seeds and hemp-derived products, the researchers studied whether dietary supplementation with these preparations could have the ability to fight chronic-degenerative diseases, characterized by persistent inflammation and oxidative stress, including cardiovascular and neurodegenerative diseases.

Studies suggest that adding 10% hemp seeds to a high-fat diet led to a significant improvement in serum parameters (i.e., a reduction in total cholesterol, LDL, and triglycerides). Daily consumption of 30 ml of hemp oil for four weeks was able to lower total plasma triglyceride (TG) levels and generate significant changes in the structure of serum cholesterol-esters (ECs) and triglycerides in healthy subjects *(Farinon, B. et al., 2020; Mikulcová, V. et al., 2017).*

Due to the alarming increase in the incidence of cancer globally, *cannabis sativa L* was among the first plants investigated for potential anticancer therapies, knowing the remarkable antioxidant properties of its more than 100 bioactive compounds. Hemp-derived extracts, especially those high in cannabidiol (CBD), exhibit important synergistic biological effects, including blocking cancer cell development, angiogenesis, and metastasis, along with promoting apoptosis. Due to these pharmacological attributes, hemp oils can be considered promising or adjuvant alternatives to conventional chemotherapy.

Figure 3 further illustrates the complexity of the tumor microenvironment (TME) and highlights the inhibitory effects exerted by CBD and THC *(Christodoulou, M.C. et al., 2025).*

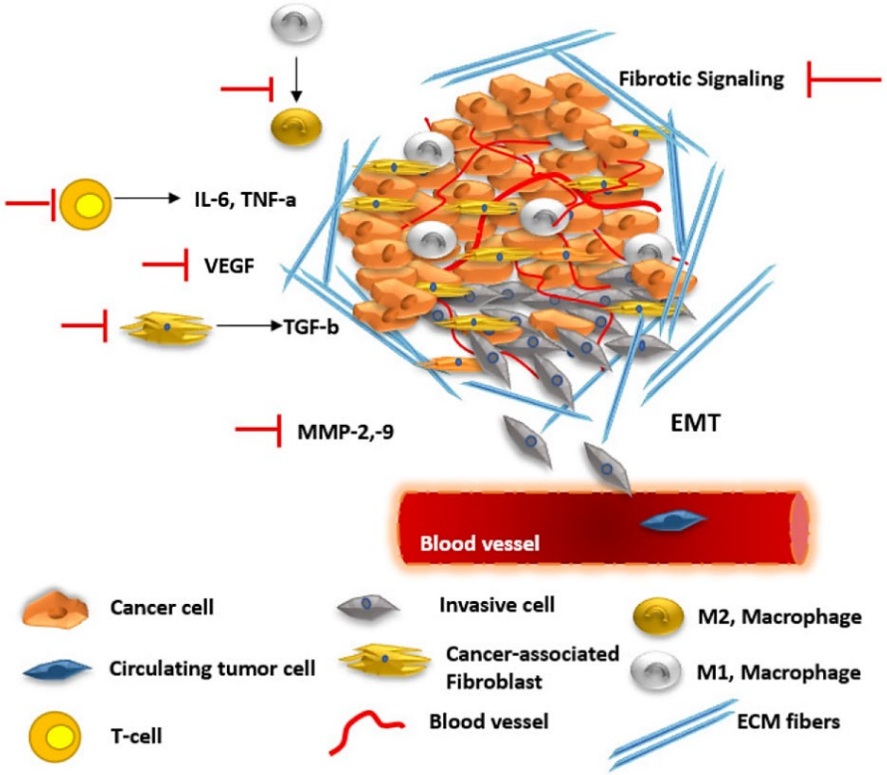

Fig. 3 - Effects of CBD and THC on the tumor microenvironment (TME). CBD suppresses pro-inflammatory cytokines (e.g., IL-6, TNF-α), helping to reduce chronic inflammation associated with tumor progression. CBD also influences macrophage polarization by shifting to the M1, antitumor phenotype (M2→M1 phenotype shift). THC can also be an immunosuppressant at high doses, reducing T cell activation and cytokine production. Both CBD and THC reduce angiogenesis by downregulating VEGF and MMPs. CBD affects EMT and negatively regulates MMP-2/9, limiting the migration and invasion of cancer cells. Limited research suggests that cannabinoids may reduce fibrotic signaling and modulate stromal support for tumors, potentially altering tumor stiffness and invasiveness. Cancer-associated fibroblasts, CAF; Cannabidiol, CBD; interleukin-6, IL-6; epithelial-mesenchymal transition, EMT; matrix metalloproteinases, MMP; tumor necrosis factor alpha, TNF-α; Δ9 - tetrahydrocannabinol, THC; vascular endothelial growth factor, VEGF

(https://www.mdpi.com/cancers/cancers).

The antiviral applications of cannabis and its bioactive compounds have been studied, especially in the context of SARS-CoV-2, while also examining their therapeutic potential. Cannabinoids can prevent virus

penetration, influence immune system responses (e.g., by reducing pro-inflammatory cytokines by activating CB2/PPARγ), and decrease mental stress associated with COVID-19. The finding suggests that CBD could alter the body's immune response by stimulating the CB2 receptor, specifically by reducing inflammation and adjusting immune responses to viral infection, figure 4 *(Qin, X. et al., 2025).*

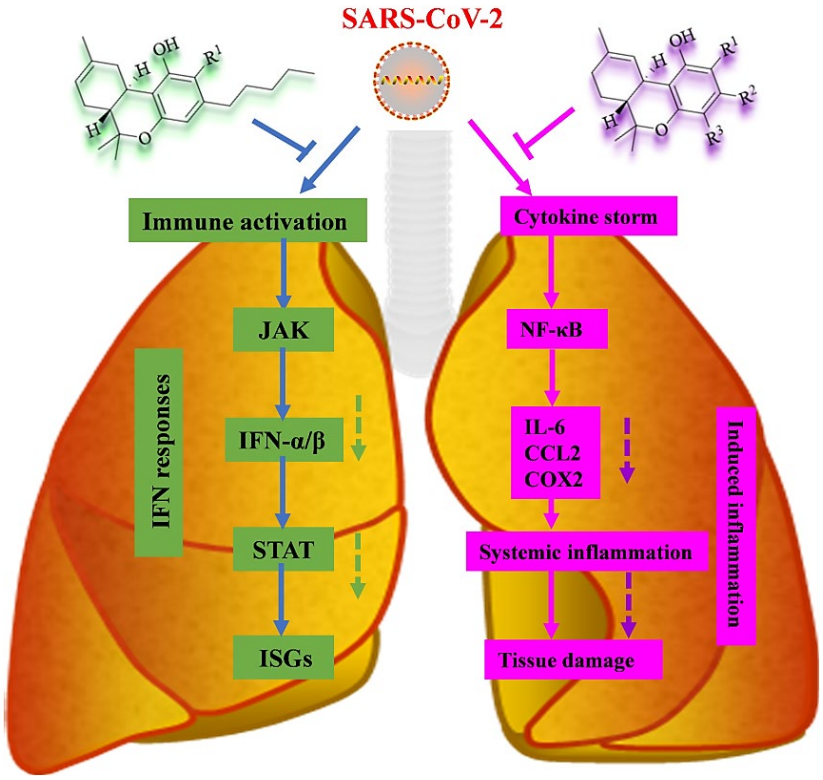

Fig. 4 - An outline of immune signaling (left) and major inflammatory signaling (right) is shown, annotated with the known mechanisms by which SARS-CoV-2 activates and suppresses signals (dotted line)
(Qin, X. et al., 2025)

Another analysis showed that consumption of hemp seed oil for 8 weeks did not decrease plasma concentrations of IL-6 and TNF-α in the group of patients with many patients undergoing maintenance hemodialysis (MHD), instead some clinical studies have shown that Omega-3 polyunsaturated fatty acids have anti-inflammatory effects in HD patients *(Khosravi, M. et al., 2021).*

The benefit of hemp as a nutritional supplement is that it can enrich the consumer's diet. Hemp extracts, such as CBD, are currently used as dietary supplements. There is an interesting pharmaceutical and dietary supplement and can be added to foods to complement the nutritional value *(Lin, Y., et al., 2021).* CBDIt has also been shown that daily oral administration of hemp seed oil on a mouse model with MS can have positive effects on the treatment of this chronic-inflammatory and neurodegenerative disease characterized by extensive demyelination, as it can exert immunomodulatory action, especially anti-inflammatory, and improve the remyelination of the neuronal myelin sheath in the brain, with a protective effect on the central nervous system (CNS) *(Rezapour-Firouzi, S. et al., 2018).*

It is now known that the endocannabinoid system (ECS) plays an essential role in maintaining balance in the body, creating connections between all organs and systems of the body. ECS has been associated with various conditions and essential regulatory functions, including chronic inflammatory conditions and adjustment of immune homeostasis in the gut, as well as anxiety and migraines.

Although the body produces its own endogenous cannabinoids, such as anandamide and 2-arachidonylglycerol, plant-derived cannabinoids (phytocannabinoids) have been studied as promising therapeutic options in numerous fields, due to their ability to influence ECS *(Harrison, J. et al., 2019).* Figure 5 summarizes the basic molecular biology of the ECS, as well as some of the molecular effects of phytocannabinoids *(https://ars.els-cdn.com/content/image)*.

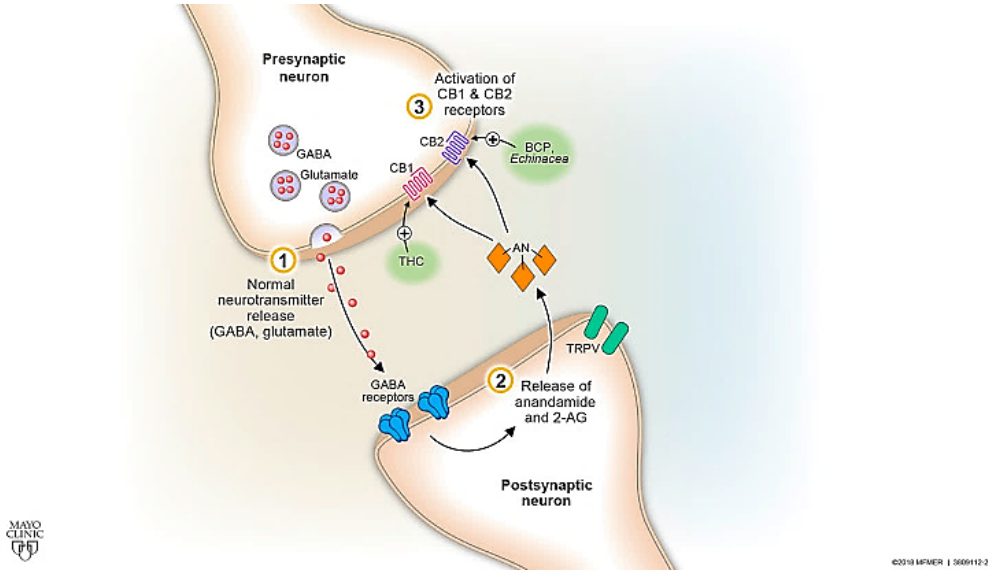

Fig. 5 - Modulation of the endocannabinoid system by phytocannabinoids. The figure illustrates how the endogenous cannabinoids anandamide (AN) and 2-arachidonylglycerol (2-AG) interact with cannabinoid receptors 1 and 2 (CB1 and CB2) that are associated with the G protein in presynaptic neurons in both the central and peripheral nervous systems. The compounds marked in green represent common plant cannabinoids and other plant components in hemp oils, which have been shown to influence natural endocannabinoids in one way or another, either by altering the activity of CB receptors (e.g., the agonist effect of tetrahydrocannabinol [THC] on CB1 receptors) or through as yet unexplained mechanisms, such as inhibition of enzymatic degradation of endocannabinoids or other forms of receptor modification. BCP stands for β-caryophyllene; GABA stands for γ-aminobutyric acid; and TRPV represents the potential transient vanilloid receptor

(https://ars.els-cdn.com/content/image)

Cannabis sativa *seeds* are low in phytocannabinoids, but are instead rich in omega-6 and omega-3 essential fatty acids, substantial amounts of γ-linolenic acid, and other nutritious antioxidants. In addition, there are also products based on "cannabis oil", which are oils derived from the marijuana plant that have high levels of THC. Table 1 summarizes these differences *(Harrison, J. et al., 2019).*

Table 1

Hemp Seed, CBD, and Cannabis Oils

(Harrison, J. et al., 2019)

Variable name:	Hemp seed oils	Hemp/CBD oils	Cannabis oils
Part of plant extracted	Seeds	Flowers and leaves of hemp plant	Flowers and leaves of marijuana plant
Main components	Omega-6 and omega-3 fatty acids, γ-linolenic acid, nutritious antioxidants	Mostly CBD and BCP with other smaller-quantity phytocannabinoids and terpenoids	Mostly THC with some CBD and other phytocannabinoids and terpenoids
THC levels	None	<0.3% Dry weight	>0.3% Dry weight (often very high amounts such as 80%)
CBD levels	Little to none	More than average cannabis plants (12%-18% CBD, often higher due to postextraction enrichment)	Lower levels (10%-15%)
Uses	Nutritional supplement, other uses of hemp such as clothing and fibers	Medicinal uses of CBD and full-spectrum hemp oils	Medicinal uses of THC

BCP = β-caryophyllene; CBD = cannabidiol; THC = tetrahydrocannabinol.

The products can be marketed as "full-spectrum" formulas, dietary supplements, hemp oils or CBD-enriched products, in the form of oils, capsules, soft gelatin capsules, conditioners, sprays, even chew toys

for pets. These products are marketed for a variety of uses, such as sleeping pills, pain relief, or stress reduction *(Harrison, J. et al., 2019).*

As an active, plant-based, easily extractable biological compound with a high therapeutic index and a good safety profile, CBD is currently marketed both as a dietary supplement derived mainly from hemp, subject to ever-evolving legislation and regulatory actions, and as a medicine, such as Epidiolex (CBD only) and Sativex (THC and CBD in a 1:1 ratio), with specific indications of worldwide approval. Epidiolex is currently approved by both the European Medical Agency and the Food and Drug Administration (FDA) against seizures associated with Lennox-Gastaut syndrome or Dravet in patients 2 years of age and older, based on high-quality scientific evidence from randomized controlled clinical trials *(Cerino, P. et al., 2021; EMCDDA, 2018*).

CONCLUSIONS

The growing demand for dietary supplements with increased efficiency in managing various health problems and the complexity of the structure of hemp (Cannabis sativa L.) have contributed to the increase in its use in the nutraceutical field. The plant has also received increased attention from scientists who have been looking at potential alternatives to conventional medicines.

Numerous studies confirm the antioxidant and anti-inflammatory effects of hemp seeds and hemp products. Hemp seeds stand out for their remarkable content of quality proteins, including albumin and edestine which contribute to an exceptional nutritional value. They are also rich in healthy lipids with a high content of polyunsaturated fatty acids, such as linoleic acid (omega-6), alpha-linolenic acid (omega-3) and some vitamins (vitamins E, D and A).

Extracts made from hemp, especially those containing a high amount of cannabidiol (CBD), have important complex biological effects, including blocking the growth of cancer cells.

The antiviral applications of cannabis and its bioactive compounds have been studied especially in the context of SARS-CoV-2, as cannabinoids can prevent the penetration of the virus and influence immune system responses. Hemp seed oil may have positive effects on the treatment of chronic-inflammatory and neurodegenerative diseases.

The results of research suggest that traditional medicine is used as an adjunct therapy to modern medicine. The bioactive compounds in each part of the hemp plant lead to a future trend to capitalize on the entire plant, in the context of changing the diet globally and managing waste as efficiently as possible.

ACKNOWLEDGEMENT:

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STUDIES AND RESEARCH ON THE TECHNOLOGICAL PROCESS OF REMOVING SOLID PARTICLES FROM WASTEWATER OF A RECIRCULATING AQUACULTURE FISH FARMING SYSTEM, BY USING TECHNICAL MECHANICAL FILTRATION EQUIPMENT

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STUDII ȘI CERCETĂRI ASUPRA PROCESULUI TEHNOLOGIC DE ÎNDEPĂRTARE AL PARTICULELOR SOLIDE DIN APĂ REZIDUALĂ A UNUI SISTEM ACVACOL RECIRCULANT DE CREȘTERE A PEȘTILOR, PRIN UTILIZAREA UNUI ECHIPAMENT TEHNIC DE FILTRARE MECANICĂ

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ABSTRACT

For recirculating aquaculture system (RAS) maintaining physico-chemical characteristics of the water at an optimum level for breeding species, is one of the main goals to be achieved in order to talk about what a successful aquaculture means. Technological developments in the field of mechanical filtration in recent decades have contributed in a decisive way in terms of waste water filtration process within a recirculating system, with the aim to improve its quality, but not least significant reduction of waste that are released into the environment. This paper aims to develop a description of the situation that exists both global and national levels on the range of mechanical water filtration equipment that are used in a RAS.

REZUMAT

Pentru sistemul de acvacultură cu recirculare (SAR), menținerea caracteristicilor fizico-chimice ale apei la un nivel optim pentru speciile de reproducere este unul dintre principalele obiective care trebuie atinse pentru a vorbi despre ce înseamnă o acvacultură de succes. Dezvoltările tehnologice în domeniul filtrării mecanice din ultimele decenii au contribuit într-un mod decisiv în ceea ce privește procesul de filtrare a apelor uzate în cadrul unui sistem de recirculare, cu scopul de a îmbunătăți calitatea acestora, dar nu în ultimul rând de a reduce semnificativ deșeurile care sunt eliberate în mediu. Această lucrare își propune să dezvolte o descriere a situației existente atât la nivel global, cât și național, privind gama de echipamente mecanice de filtrare a apei utilizate într-un SAR.

INTRODUCTION

In order that a recirculating acvacol system to be economic, it must have reliable and efficient technology that are able to maximize the production *(Steven T. Summerfelt, 1998)*. The technological installations that are found in a recirculating system must ensure the optimal conditions for the growth and development of crop species, by reconditioning the water which is recycled within the system (*Interdonato Filippo, 2012; Victor Cristea, Iulia Grecu, Cornel Ceapa, 2002)*.

One of the main problems of recirculating systems is the problem of removing of solid particles. It was estimated that around 60% of the food introcuced into the system remains unconsumed and is transformed in residual solids *(Michael P. Masser, James Rakocy and Thomas M. Losordo, 1999).*

According to him *(Ariel. E and Jutta. P, 2014),* the quantity of waste from a recirculating system is directly proportional to the fish production within the system *(Interdonato Filippo, 2012).*

Still from the design stage of a recirculating system, focus must fall on controlling and removing the solid particles coming from the unconsummated feed, faecal matter and bacterial biomass, to prevent in this way the supplementary consumption of oxygen, the uncontrolled increase of the amount of carbon dioxide

and of the ammoniacal nitrogen, compounds particularly toxic for fish *(Joanna G. Twarowska, 1997; Keith Jeffery, 2011; Steven T. Summerfelt, 1998)*.

To reduce the amount of solids in the tanks for growth, solids that can negatively affect the physical and chemical factors of the water, is needed the use of mechanical filtration equipment, dimensioned so as to be capable of removing the organic matter accumulated in the system *(Thomas M. Losordo, Michael P. Masser and James Rakocy, 1998)*.

Mechanical filtration is one of the major processes of controlling the solid particles from the recirculating system *(Shulin Chen și Ronald F. Malone 1991)*. The role of mechanical filtration as the first water filtration process of RAS is all the more important because of it depends the success of all other stages which will follow in the filtering process *(James M. Ebeling).*

The principle underlying the mechanical filtration refers to the fact that the wastewater coming from the growing tanks passes through a filtering material which is intended to retain the solid particles from water *(Samir Ahmad Ali, 2012).* The filtering material present in filters consists of: sand, gravel or various types of sieves made textile materials or non-corrosive metals *(Michel Couturier et. all 2009).*

To remove suspended solids in recirculating systems *(Losordo et al., 1998)* affirm that are specifically used two types of mechanical filters: drum filter and sand filter *(Pop Augustin, colab.2009; Alessandro Moretti, 2005)*.

MATERIALS AND METHODS

In the field of mechanical filtration at present there are a number of devices that can cover a wide range of applications in the acvacol field, the way in which are classified the filtering processes which are used particularly in aquaculture is made according on the nature of the filtering medium: filtration with sieves and filtration with granular agents *(Brinker, A., Bergheim, A.., 2005).*

As regards the equipments for mechanical filtering with sieves, the largest shares are occupied by the following types of filters: axial filters with rotating sieves, radial filters with rotating sieves and chain filters with sieve. Among the consecrated companies manufacturing mechanical filters for recirculating acvacole systems we mention: Hydrotech - Sweden, FIAP – Germany, Faivre – France, Akva- Denmark.

Nationally one of the companies producing installations designed to the acvacol sector is the company EuroCar - Oradea, and one of the products made by them, which was successfully implemented in several fish farms in Romania is the drum filter.

Mechanical filtration with sieves is the most common method in the filtering process widely in commercial Aquaculture and research.

The mode of action of these type of filters is that the water loaded with solid particles passes through a system of sieves, the sieves retaining only the particles of equal size or larger than the sieve meshes *(Fred Wheaton, 2002)* Sieves dimensioning is based on the charging degree of the water with solid particles (TSS) and of the granulometric composition of them *(Bura Marian, 2008).*

Currently at a worldwide there are no farms with the recirculation of the water evacuated from the tanks which does not use the filters with microsieves, this and because they occupy a relatively small space, not require the same physical effort as in the case of the sumps when carrying out the maintenance and cleaning works *(Fred Wheaton, 2002).* In the case of filtering with sieves the filtering capacity is given by the mesh size of the sieve ranging between 40 – 100 μm, and according to Jelenna Stokic, 2012 between 60 - 200 μm *(Jelena Stokic, 2012).* Cripps and Bergheim, 2000 quoted by *(Couturier et al., 2009),* concluded that the use of filtration equipment with microsieves with a mesh size less than 60 mm, are not recommended due to the risk of the clogging phenomenon *(Keith Jeffery, Nicholas Stinton & Tim Ellis, 2011).*

The filters with rotary sieves, according to (Tchobanoglous and Burton, 1991), represent the most efficient solution to the conventional alternative by sedimentation of solid particles and for this reason these have been successfully implemented on the acvacole farms *(Samir Ahmad Ali, 2012).*

The functioning of the filters with rotary sieves, no matter if we speak of the axial or radial ones in both cases these will work only if they are partially immersed in the water to be filtered *(James H. Tidwell, 2012).* To clean strainers, both the radial filters with rotary sieve and the axial filters with rotary sieve are equipped with a system of spraying nozzles disposed above the drum or in the case of axial filter the nozzles are fixed on the downstream side of the sieve, in this way it is done the washing of the retained solid particles *(Odd- Ivar Lekang, 2007).*

Drum filtering is the predominant technology for the removal of solids with the widest spread worldwide and as the degree of use in recirculating *systems (James M. Ebeling, Carla F. Welsh, Kata L.*

Rishel, 2006). This is due primarily to the filtering capacity that can be adjusted according to the charging with solid suspensions of the recirculating system. Normally, the mechanical filters are able to remove the solid particles larger than 40 - 100 μm, whilst states that the mechanical filters are designed to remove only can particles larger than 80 μm *(Odd- Ivar Lekang, 2007)*. It is specified in the literature that a drum filter can remove about 40% of the total of solids in suspension *(Henrik Mortensen, 2014*).

The working principle of the drum filter is relatively simple, water loaded with solid particles in suspension (TSS) is entering the drum filter in an axial direction and is coming out filtered in a radial direction. During the filtering process as the network mesh of sieve from the drum filter is loaded with solids the water level rises, switching on the spray equipment. Then washed solid material is collected in a trough and discharged outside the system *(Bura Marian, 2008).*

Usually, to wash the sieves of a drum filter is used an amount of 0.2 to 2% of the volume of water through the use of the high-pressure water jet [3]. The main disadvantage of this type of filter is the costs of maintenance and operation of it *(James H. Tidwell, 2012).*

Fig. 1 - Radial filter with rotating

RESULTS

The experiments on the mechanical water filtration installation were carried out under laboratory conditions by integrating this technical equipment into the circuit of an aquaculture system. The utilities necessary for the experiments, namely the electricity supply, fresh water supply and waste water evacuation, were provided.

The mechanical water filtration system has the role of ensuring the proper quality of the water supplied to the growth tanks. This is achieved using a rotating drum type filter.

The rotating screen is a high-capacity filter with much smaller dimensions than other screens used in solid-liquid separation. The filtration rate is five times higher in the case of this type, compared to static screens, and the possibility of it being blocked by residues is practically nil because they have a self-cleaning system.

The water flow with suspended solid particles enters the drum axially and exits filtered in a radial direction, through the mesh network of the screen.

The maximum filtration capacity of this screen is 50 m^3/hour.

The physical and chemical characteristics of the water at the exit of the mechanical filter are presented in table 1.

Table 1

The physical and chemical characteristics of the water at the exit of the mechanical filter

Waste	40 μm	60 μm	90 μm
Total phosphorus	65 – 84 %	50 – 80 %	45 – 75 %
Total nitrogen	25 – 32 %	20 – 27 %	15 – 22 %
Solids in suspensions	60 – 91 %	55 – 85 %	50 – 80 %

CONCLUSIONS

To have a successful aquaculture first of all of performant equipments, competitive, that to maximize the fish production.

To increase the fish production and minimize any loss, we need that the water recycled through system to be correctly filtered.

For this reason it is essential to know which are the most efficient equipment for the removal of the solid particles within a recirculating system and for this we must to know what exist today on the market.

One of the most appreciated filtration equipment within a RAS, due to its effectiveness is the drum filter.

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INTEGRATED MECHANICAL AND METABOLIC ENGINEERING STRATEGIES FOR HIGH-CELL-DENSITY CULTIVATION OF *SACCHAROMYCES CEREVISIAE* IN STIRRED-TANK BIOREACTORS: A CRITICAL REVIEW

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STRATEGII INGINEREȘTI MECANICE ȘI METABOLICE INTEGRATE PENTRU CULTIVAREA LA DENSITATE RIDICATĂ A SACCHAROMYCES CEREVISIAE ÎN BIOREACTOARE CU AGITARE MECANICĂ: O ANALIZĂ CRITICĂ

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ABSTRACT

Saccharomyces cerevisiae remains the dominant eukaryotic model in industrial biotechnology, with extensive applications in food, beverage, pharmaceuticals, and biofuels. Achieving high-cell-density cultivation (HCHC) in stirred-tank bioreactors requires a delicate integration of mechanical engineering strategies (impeller design, hydrodynamics, gas-liquid mass transfer) with metabolic regulation (substrate feeding, nutrient balance, mitigation of the Crabtree effect). This review provides a comprehensive and critical synthesis of recent advances in STR design and operation for yeast cultivation, highlighting the interplay between oxygen transfer dynamics, shear forces, and metabolic adaptations. Recent advances highlight the role of process analytical technology (PAT) and computational fluid dynamics (CFD) in enhancing real-time monitoring, improving predictive modelling, and facilitating more reliable scale-up of yeast cultivation processes.

REZUMAT

Saccharomyces cerevisiae rămâne modelul eucariotic dominant în biotehnologia industrială, având aplicații extinse în domeniul alimentar, farmaceutic și energetic. Obținerea unor culturi la densitate celulară ridicată (HCDC) în bioreactoare cu agitare mecanică presupune integrarea atentă a strategiilor inginerești mecanice (designul agitatoarelor, hidrodinamica, transferul de masă gaz-lichid) cu reglarea metabolică (hrănirea cu substrat, echilibrul nutrițional, reducerea efectului Crabtree). Această analiză oferă o sinteză cuprinzătoare și critică a progreselor recente în proiectarea și operarea bioreactoarelor cu agitare mecanică pentru cultivarea drojdiilor,subliniind interacțiunea dintre dinamica transferului de oxigen, forțele de forfecare și adaptările metabolice. Se evidențiază rolul tehnologiilor PAT și al dinamicii fluidelor computaționale (CFD) în monitorizarea avansată, modelarea predictivă și susținerea scalării fiabile a proceselor de cultivare a drojdiilor.

INTRODUCTION

The yeast *Saccharomyces cerevisiae* has been the heart of human civilization for millennia. Its use in bread, beer, and wine production dates back to ancient Egypt and Mesopotamia *(Parapouli et al., 2020*). Today, it remains indispensable not only for traditional food and beverage fermentation but also for modern biotechnology sectors, including bioethanol, biopharmaceuticals, fine chemicals, and heterologous protein-production *(Nandy & Srivastava, 2018; Stanbury et al., 2016)*. The global industrial yeast market has grown steadily, with bioethanol alone accounting for more than 100 bilion liters annually, much of it produced by *S. cerevisiae (Mussatto, 2010)*.

Saccharomyces cerevisiae was the first eukaryotic organism to have its entire genome sequenced *(Goffeau et al., 1996)*, reinforcing its status as both a model organism and an industrial workhorse. Its Generally Recognized As Safe (GRAS) designation makes it particularly attractive for pharmaceutical and food applications *(Parapouli et al., 2020)*. However, high-cell-density cultivation (HCDC), often targeting biomass concentrations >50 g/L dry cell weight (DCW), remains technically demanding. The major

engineering bottleneck in STR-based cultivation is oxygen transfer. Oxygen solubility in aqueous broths is extremely low (~7–8 mg/L at 30 °C), while yeast demands high oxygen uptake rates for biomass and metabolite production *(Garcia-Ochoa et al., 2010)*. Scale-up from 5 L laboratory STRs to >5000 L industrial bioreactors typically reduces kLa by more than 50%, while increasing mixing times tenfold *(van't Riet & Tramper, 1991; Shuler & Kargi, 2017)*. These gradients create metabolic heterogeneity, limiting process robustness *(Arulrajah et al., 2025)*.

On the metabolic side, yeast exhibits the Crabtree effect: when glucose concentrations exceed ~40 g/L, fermentative metabolism dominates even the presence of oxygen, resulting in ethanol accumulation and reduced biomass yields *(Malairuang et al., 2020)*. Overcoming this requires controlled feeding strategies, nutrient supplementation, and, in some cases, immobilization approaches *(Călinescu et al., 2012)*.

And of course, recent advances in digitalization are reshaping the engineering of yeast bioprocesses. Computational fluid dynamics (CFD) has emerged as a powerful tool to resolve spatial heterogeneities by simulating oxygen distribution, mixing patterns, and localized shear environments within large-scale bioreactors *(Susukida et al., 2025)*. In parallel, process analytical technology (PAT) provides real-time, data-rich monitoring of key variables such as dissolved oxygen, pH, and biomass, enabling dynamic adjustments of cultivation conditions *(Brudes et al., 2016; Yousefi- Darani et al., 2021*).

The convergence of CFD-based modelling with PAT-driven monitoring establishes the foundation for predictive and adaptive control strategies, thereby bridging classical fermentation engineering with modern data-driven approaches for robust STR-based yeast cultivation.

BIOREACTOR HYDRODYNAMICS AND OXYGEN TRANSFER

Stirred-tank bioreactors (STRs) continue to represent the benchmark configuration for aerobic yeast processes owing to their scalability and operational flexibility. Within these systems, hydrodynamic performance is largely dictated by impeller geometry, baffle arrangement, and power input, all of which govern oxygen transfer and mixing efficiency. Radial-flow impellers such as Rushton turbines are capable of delivering high gas dispersion, achieving kLa values in the range of 200-400 h^{-1} at 600 rpm in laboratory-scale reactors; however, this performance is often accompanied by elevated shear stresses than can compromise cell viability *(van't Riet & Tramper, 1991; Garcia-Ochoa et al., 2010)*. In contrast, axial-flow shear loads, though at the expense of lower oxygen transfer rates, typically around 150 h^{-1}. Pitched-blade turbines provide an intermediate solution, balancing mixing efficiency with shear tolerance, while multi-impeller arrangements are frequently employed in tall industrial vessels to ensure homogeneity across large working volume *(Stanbury et al., 2016)*.

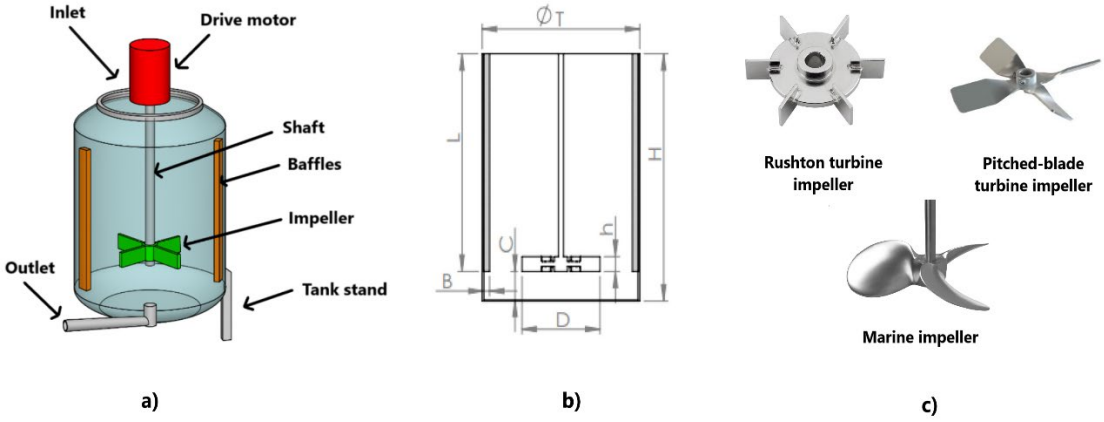

Fig. 1 - Schematic representation and dimensional drawing of the stirred-tank bioreactor (a–b), and examples of impeller geometries: (a) Rushton turbine impeller (radial-flow), (b) pitched-blade turbine impeller (mixed-flow), and (c) marine impeller (axial-flow)
(adapted from Torotwa, I. et al. 2018)

As illustrated in Figure 1, the stirred-tank bioreactor is typically equipped with baffles and a centrally mounted impeller, whose geometry plays a decisive role in shaping the hydrodynamic environment. Among the most widely adopted designs, the Rushton turbine (radial-flow) is recognized for its ability to promote intense gas dispersion and high oxygen transfer rates, though often at the cost of increased shear stress. In contrast, pitched-blade turbines generate a mixed-flow pattern that provides a more balanced compromise between oxygen availability and mechanical stress, making them suitable for processes involving moderately

shear-sensitive microorganisms. Marine impellers, characterized by their axial-flow configuration, are frequently applied when reduced shear conditions are prioritized, albeit with comparatively lower kLa values.

The selection of impeller design thus directly influences mixing efficiency, oxygen transfer capacity, and ultimately the physiological response of *Saccharomyces cerevisiae*. In this context, Tabel 1 summarizes reported kLa values for *Saccharomyces cerevisiae* in stirred-tank bioreactors of different scales, explicitly highlighting the influence of impeller design in conjunction with agitation and aeration conditions.

Tabel 1

Reported kLa values in stirred-tank bioreactors for Saccharomyces cerevisiae and related systems (with impeller types)

Scale / Bioreactor	Agitation (rpm)	Aeration (vvm)	kLa (h^{-1})	Impeller type / configuration	Notes / Organism & medium	Reference
5 L laboratory STR	300	1.0	~120	Rushton turbine (radial-flow)	Standard yeast cultivation / aqueous medium	Zhuang et al., 2021
5 L laboratory STR	600	1.5	300–350	Rushton turbine (radial-flow)	High agitation, enhanced oxygen transfer	Garcia-Ochoa et al., 2010
20 L pilot STR	450	1.0	~200	Pitched-blade turbine (mixed-flow)	Pilot-scale yeast cultivation	Suresh et al., 2009
5000 L industrial STR	150	0.5	< 50	Marine impeller (axial-flow)	Industrial scale, low shear operation	van't Riet & Tramper, 1991
5 L laboratory STR	250	~5 L/min airflow	~20	Rushton / propeller impeller	Bench-top STR, reported kLa in s^{-1} converted to h^{-1}	Ramírez et al., 2020
Laboratory fermenter	Variable	-	-	Rushton vs pitched-blade	Comparative analysis of kLa under different setups	Paciello & Parascandola, 2020
STR (general review)	-	-	-	Hollow-blade impeller	Improved gas handling reported	Schaepe et al., 2013
STR with multiple impellers	400-800	-	+23–77% (gain)	Dual Rushton turbines	Performance increase compared to single impeller	Karimi et al., 2013

As shown in Tabel 1, reported kLa values for *Saccharomyces cerevisiae* in stirred-tank bioreactors vary substantially across scales and impeller designs. Laboratory-scale systems equipped with Rushton turbines often achieve high oxygen transfer rates. They can exceed 300 h^{-1} under high agitation *(Garcia-Ochoa et al., 2010)*, while moderate conditions yield ~120 h^{-1} *(Zhuang et al., 2021)*. Pitched-blade turbines in pilot reactors typically reach ~200 h^{-1} *(Suresh et al., 2009)*, whereas industrial STRs with marine impellers operate below 50 h^{-1} due to lower agitation and aeration *(van't Riet & Tramper, 1991)*. Comparative studies confirm the influence of geometry, with pitched-blades providing lower shear than Rushtons *(Paciello & Parascandola, 2020)*, dual Rushtons improving transfer efficiency *(Karimi et al., 2013)*, and hollow-blade designs enhancing gas handling *(Schaepe et al., 2013)*. Overall, impeller selection remains a key determinant of oxygen transfer and shear environment in yeast bioprocesses.

MECHANICAL STRESS AND YEAST PHYSIOLOGY

In stirred-tank systems, the physiological impact of hydrodynamics on *Saccharomyces Cerevisiae* depends strongly on energy dissipation and the flow field set by impeller design. Continuous-culture

experiments spanning mean specific energy dissipation rates from ~0.045 to 6 W kg^{-1} reported only transient, sublethal perturbations at the upper end, indicating high shear tolerance of brewing yeast under STR conditions *(Boswell et al., 2003)*. High-cell-density runs with dual Rushton turbines at 2–4 W kg^{-1} likewise maintained robust growth and productivity, consistent with yeast's resilience to the shear levels typical of laboratory STRs *(Malairuang et al., 2020)*.

Conversely, low-shear scale-up strategies that fix $\bar{\varepsilon}$ at ~0.10 W kg^{-1} across 5–3000 L have achieved comparable ethanol productivities, illustrating that oxygen supply can be decoupled from aggressive mixing when mass-transfer is engineered appropriately (*Beigbeder et al., 2021)*. Local stress still matters: controlled devices show viability drops beyond ~1.3–2.8 kPa shear stress, and regions behind radial turbines can exhibit very high local dissipation compared with the vessel average *(Daub et al., 2014)*. Together these data indicate that impeller choice governs the shear/oxygen trade-off, but yeast remains comparatively tolerant over the $\bar{\varepsilon} \approx$ 0.1–4 W kg^{-1} window commonly used in aerobic processes.

Tabel 2

Shear tolerance of *Saccharomyces cerevisiae*

Energy dissipation / Shear	Impeller / System	Observed effect on viability / growth	Notes	Reference
0.045–6 W kg^{-1}	Aerated STR (continuous)	No lasting viability loss; only transient sublethal signals at >~4.5 W kg^{-1}	Brewing yeast; multiparameter flow cytometry	Boswell et al., 2003
2–4 W kg^{-1}	Dual Rushton turbines (5 L)	High-cell-density growth sustained	Robust performance	Malairuang et al., 2020
~0.10 W kg^{-1} (fixed across scales)	STRs 5–3000 L	Comparable ethanol productivities across scales; no evidence of shear-related loss	Low-shear scale-up criterion	Beigbeder et al., 2021
1.3–2.8 kPa (local shear stress)	Controlled shear device	Onset of viability decrease above threshold	Shear reported as stress (Pa), not W kg^{-1}	Lange et al., 2001
-	STR/shake systems	Highlights heterogeneity of local dissipation; relevance for hot-spots	Method to estimate e_{max} in small vessels	Daub et al., 2014
local dissipation behind blades	Rushton region	Very high local dissipation possible near blades vs vessel average	-	Hewitt et al., 2010

Overall, hydrodynamic control, rather than agitation intensity alone, governs *Saccharomyces cerevisiae* performance, with impeller geometry setting the operative trade-off between oxygen delivery and mechanical load. Practical scale-up should target the required oxygen transfer at the lowest feasible mean dissipation while limiting local hot-spots via impeller selection, multi-impeller configurations, and baffling.

METABOLIC AND NUTRITIONAL STRATEGIES

Metabolic control must be co-engineered with hydrodynamics. In batch cultivation on high initial glucose (≈50 g L^{-1}), *S. cerevisiae* rapidly enters the Crabtree regime, diverting carbon to ethanol at the expense of biomass, a pattern well documented in standard practice *(Stanbury et al., 2016)*. Glucose-limited fed-batch strategies that maintain the residual substrate below the Crabtree threshold (<0.5g L^{-1}) suppress overflow metabolism and substantially increase cell density, an outcome mirrored by maltodextrin/dextrin feeding that delivers glucose gradually and supports high-cell-density cultivation *(Malairuang et al., 2020)*.

Beyond suspended cultures, immobilization (e.g., calcium-alginate or polyacrylamide matrices) stabilizes the biocatalyst and can improve ethanol productivity under industrial conditions *(Călinescu et al., 2012)*, consistent with classic reports of higher production rates and multi-cycle reusability for alginate-entrapped yeast.

Meanwhile, cell-retention membrane bioreactors (MBRs) provide an alternative route to HCDC and product accumulation; although widely deployed for oleaginous yeasts, they illustrate how decoupling growth from washout can outperform conventional STRs for certain products *(Koruyucu et al., 2023)*.

Tabel 3

Feeding and immobilization strategies

Strategy	Substrate/ Control Target	Max DCW (g L^{-1})	Ethanol accumulation	Reference
Batch	Glucose 50 g L^{-1}	25-30	High	Stanbury et al., 2016
Fed-batch	Glucose maintained <0.5 g L^{-1}	45-50	Low	Malairuang et al., 2020
Fed-batch	Maltodextrins / dextrin feeding	55-60	Minimal	Malairuang et al., 2020
Immobilized	Glucose 80 g L^{-1}	>40	Moderate	Călinescu et al., 2012

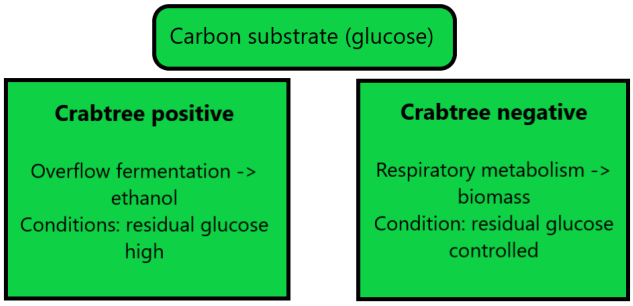

Fig. 2 - Metabolic routing under high vs controlled residual glucose: overflow fermentation versus oxidative growth in S. cerevisiae

(adapted from Dashko, S.et al.2014)

SCALE-UP AND INTEGRATIVE SOLUTIONS

Scaling to m^3 vessels amplifies transport non-linearities: mixing slows and DO/pH/substrate gradients appear, driving metabolic heterogeneity as cells cycle through aerobic-anaerobic microenvironments *(Arulrajah et al., 2025)*. CFD helps localize the origin of these hot and cold spots and predicts shear/mixing distributions around impellers and gas cavities *(Zhang et al., 2019; Susukida et al., 2025)*. Practically, two levers dominate: (i) oxygen transfer, improved by oxygen enrichment of moderate overpressure, and (ii) bulk mixing, improved by axial or multi-impeller shafts and CFD guided sparger/impeller placement *(Garcia-Ochoa et al., 2010; Zhuang et al., 2021)*.

In parallel, PAT (Raman/fluorescence probes with soft sensor models) enables real-time state estimation and faster corrective action; coupled with data-driven control, “smart” bioreactors move from reactive to predictive operation *(Bruder et al., 2016; Yousefi-Darani et al., 2021; Zhuang et al., 2021)*. Finally, hybrid configurations mitigate scale constraints: immobilized yeast stabilizes performance under stresses, while cell-retention membrane systems sustain high cell density and product accumulation (Călinescu et al., 2012; Koruyucu et al., 2023).

To illustrate how the engineering maneuvers proposed here (CFD-guided impeller/sparger design and PAT-assisted control) address scale-dependent heterogeneity, we include two CFD examples. Figure 3 visualizes where dissipation and shear concentrate in a double-impeller STR, explaining hot spots, recirculation boundaries, and low-shear cores. Blade-wake/tip-vortex hot spots and the impeller-impeller interaction zone delineate recirculation boundaries and a low-shear core, providing a mechanistic basis for axial or multi-impeller layouts, spacing/clearance optimization, and targeted sparger placement *(Ebrahimi et al., 2019)*.

Meanwhile, figure 4 shows logarithmic shear-rate fields with streamlines across geometries and speeds, highlighting boundary layers at baffles, recirculation cells, and stagnation pockets. High shears localizes near impeller blades and within the baffle boundary layer, while recirculation cells and stagnation pockets appear in the bulk and depend on impeller geometry/clearance; these patterns motivate CFD-guides choices of impeller type/spacing and sparger layout, completemented by PAT for real time supervision *(Šafarič et al., 2019)*.

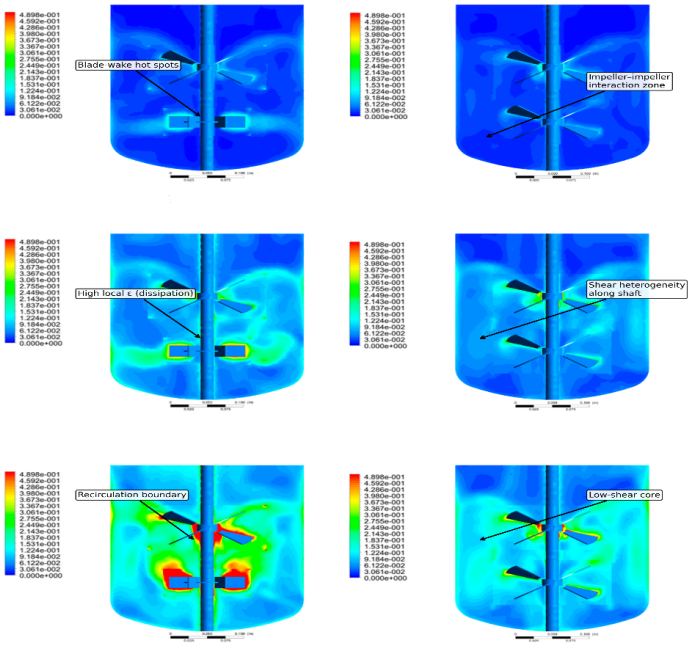

Fig. 3 - CFD-derived turbulence/energy-dissipation fields in a double-impeller STR
(adapted from Ebrahimi,M. et al. 2019)

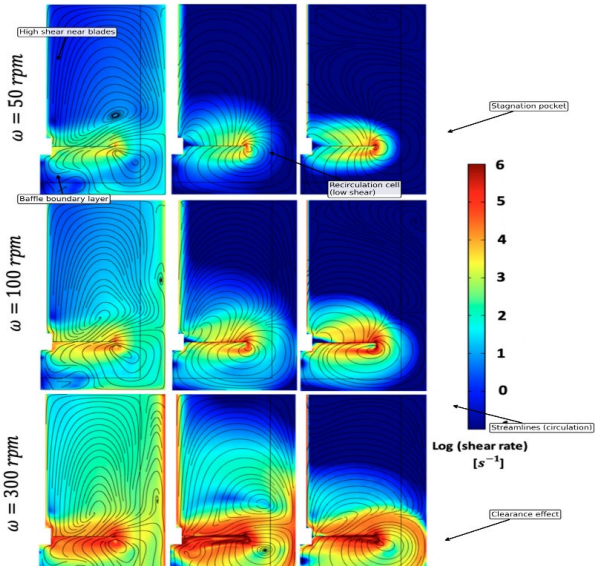

Fig. 4 - Log shear-rate contours with in-plane streamlines in a stirred vessel
(adapted from Šafarič et al., 2019)

CONCLUSIONS

High-cell-density cultivation of Saccharomyces cerevisiae in stirred-tank bioreactors represents a complex interplay between hydrodynamic performance and metabolic regulation. The synthesis of available data indicates that impeller geometry is a primary determinant of the balance between oxygen transfer efficiency and mechanical stress. Rushton turbines (radial-flow) consistently deliver the highest volumetric oxygen transfer coefficients (kLa values often exceeding 300 h^{-1} under laboratory conditions), yet they impose elevated local shear stresses than can compromise cell viability at scale, while marine impellers ensure gentle mixing at the expense of oxygen transfer. Evidence indicates that pitched-blade turbines, or hybrid multi-impeller systems, represent the most effective compromise, sustaining robust growth and minimizing ethanol overflow. From a metabolic standpoint, the most effective strategy remains glucose-limited fed-batch cultivation, witch consistently suppresses the Crabtree effect and allows biomass concentrations above 50 g/L dry cell weight. Also, immobilization and retention systems further stabilize culture performance under stress conditions, enabling multi-cycle operation and supporting product accumulation in case of high-density regimes. Supported by advanced CFD modelling and PAT- driven

monitoring, these configurations provide a scientifically robust basis for a reliable scale-up and a sustainable operation of industrial yeast bioprocesses.

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GIS TECHNOLOGY AND ITS APPLICATIONS IN ENVIRONMENTAL ENGINEERING
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TEHNOLOGIA GIS ȘI APLICAȚIILE ACESTEIA ÎN INGINERIA MEDIULUI

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ABSTRACT

Geographic Information Systems (GIS) technology plays an increasingly important role in environmental engineering, providing an efficient framework for collecting, managing, analyzing, and visualizing spatial data. This technology enables environmental professionals to better understand the relationships between natural phenomena and human activities, thus contributing to informed and sustainable decision-making. The present article analyzes the fundamental concepts of GIS technology and highlights its main applications in the field of environmental engineering. Concrete examples are presented to demonstrate how GIS can support predictive modeling, real-time monitoring of resources, and the assessment of the environmental impact of human activities. The conclusion emphasizes that GIS technology is essential not only as a technical tool but also as a strategic support mechanism for the development of environmental policies and for adaptation to climate change.

REZUMAT

Tehnologia Sistemelor Informaționale Geografice (GIS) joacă un rol tot mai important în ingineria mediului, oferind un cadru eficient pentru colectarea, gestionarea, analiza și vizualizarea datelor spațiale. Această tehnologie permite profesioniștilor din domeniul mediului să înțeleagă mai bine relațiile dintre fenomenele naturale și activitățile umane, contribuind astfel la luarea unor decizii informate și sustenabile. Articolul de față analizează conceptele fundamentale ale tehnologiei GIS și evidențiază principalele sale aplicații în ingineria mediului. Sunt prezentate exemple concrete recente care demonstrează modul în care GIS poate sprijini modelarea predictivă, supravegherea în timp real a resurselor și evaluarea impactului activităților antropice asupra mediului. Concluzia subliniază că tehnologia GIS este esențială nu doar ca instrument tehnic, ci și ca suport strategic în elaborarea politicilor de mediu și în adaptarea la schimbările climatice.

INTRODUCTION

With the development of human society, it has become evident that human activity influences the environment and is, in turn, influenced by it. Through various stages of organization, environmental quality protection, and more recently, integrated environmental management, has become a vital necessity to ensure societal prosperity and sustainable development.

Environmental management has become an essential aspect of any type of development, regardless of the scale at which environmental impacts may occur.

To ensure effective governance of all social activities, even when environmental aspects sometimes seem secondary, the need for a system of continuous monitoring and assessment of environmental quality has emerged in the form of an environmental monitoring system *(Mihăiescu, R., 2014).*

As pressures on the environment increase, it becomes increasingly clear that effective decision-making cannot be achieved without accurate and integrated information.

Within the course of human evolution, the major challenges we face today are the protection of the natural environment and the preservation of a high quality of life. In the pursuit of development activities, the assimilative capacity of environmental components (air, water, and soil) toward various forms of pollution is seldom considered.

The chaotic and unregulated nature of these activities leads to resource overexploitation, congestion, inappropriate land use, and, consequently, the deterioration of living conditions. As a result, environmental pollution has become a central issue, closely associated with high-risk areas and contexts.

Environmental Engineering constitutes a critical discipline focused on assessing, mitigating, and managing the impacts of environmental contaminants, encompassing the integrated management of water, air, and waste systems. Given the inherently spatial nature of environmental phenomena, which manifest across specific geographic locations and landscapes, it is imperative to capture and analyze their spatial dimensions.

It plays a key role today because it addresses major challenges caused by human activities on the environment and the need to move towards a sustainable development model. Through this field, innovative technological solutions and strategies are developed to prevent and reduce pollution, manage natural resources responsibly, and protect biodiversity.

The importance of this engineering discipline comes from its ability to balance economic progress with environmental conservation, thus contributing to public health and the resilience of ecosystems. In this context, using modern tools for analyzing and managing information has become essential.

Geographic Information Systems (GIS) stand out for their ability to collect, organize, analyze, and visualize complex spatial data, offering an integrated view of natural and human processes.

By combining various sources of information, such as climate, hydrological, geological, or biological data GIS helps understand ecosystem dynamics and supports decision-making based on scientific evidence *(Gajos, M., & Sierka, E., 2012*).

The integration of GIS into environmental management is increasingly necessary for a rigorous, data-driven approach. These technologies enable detailed monitoring of natural resources, precise assessment of the impacts of human activities, and identification of vulnerable areas.

Furthermore, GIS facilitates the analysis of complex interactions among demographic, socioeconomic, and environmental factors, providing support for the development of mitigation strategies and sustainable management plans *(Calka, B., & Szostak, M., 2025).* Thus, the use of GIS significantly contributes to environmental protection and the promotion of sustainable societal development. In this regard, GIS have emerged as a robust and accessible technology, capable of efficiently acquiring, integrating, and analyzing complex spatial datasets.

The convergence of GIS and environmental engineering thus facilitates the development of sophisticated environmental models and engineering solutions, underpinning the construction of adaptive decision support systems for sustainable environmental management and conservation *(Joao, E., & Fonseca, A., 1996)*.

Accordingly, GIS provides an indispensable framework for researchers, environmental managers, and engineers to investigate dynamic environmental processes, systematically monitor ecological phenomena, and simulate the responses of natural systems to both anthropogenic and natural perturbations *(GIS for civil engineering, 2010)*.

The Environmental Systems Research Institute defines Geographical Information Systems (GIS) as “a structured collection of computer hardware, software, geographic data, and personnel designed to efficiently capture, store, update, manipulate, analyze, and display all types of geographically referenced information”.

Building on this, Goodchild (1995) outlined additional defining characteristics of GIS, including: **(i)** the capacity to store and analyze spatial relationships among objects—such as intersection, adjacency, connectivity, or overlap—and to compute these relationships when required; **(ii)** the ability to manage and analyze an unlimited range of attributes associated with each object; **(iii)** a primary focus on analysis rather than on simple data storage and retrieval; and **(iv)** the integration of data from multiple sources, potentially at different scales and using diverse modes of representation *(Hamal, S., 2020).*

GIS supports environmental monitoring, assessment, and mitigation, and can also facilitate the development of environmental models. It is especially effective for organizing and analyzing environmental data. GIS serves as a core tool in environmental data systems for data transfer, retrieval, validation, and analysis. Its main components—software, hardware, data, procedures, and methods—enable people to make location-based decisions and analyses.

Fig. 1 - The components of GIS
(Perumal, M., Velumani, B., Sahasivam, A., & Kamaswany, K., 2015)

Geographic Information Systems (GIS) represent a fundamental technology in environmental engineering, due to their capacity to manage, correlate, and analyze complex spatial data. By integrating heterogeneous sources of information – from satellite imagery and digital terrain models to climatic and hydrological data – GIS facilitates the assessment of anthropogenic impacts on ecosystems and supports the development of evidence-based environmental policies.

In fields such as water resource management, pollution control, biodiversity protection, and sustainable land-use planning, GIS enables the modeling of natural processes, the identification of risk areas, and the optimization of engineering interventions. Therefore, the use of GIS in environmental engineering goes beyond mere cartography, making a significant contribution to the development of sustainable strategies for environmental protection and management.

The usefulness of GIS, particularly for decision-making and addressing environmental issues, increases with the complexity and scale of these problems. In high-risk environments, GIS can facilitate the rapid and efficient development and analysis of mitigation plans. New spatial interrelationships allow for overlays that integrate diverse demographic, socioeconomic, and environmental data, as well as information on environmental outcomes *(Shaw, N. T., & Mcguire S. K., 2017).*

The present article provides a comprehensive analysis of the fundamental concepts underlying Geographic Information Systems (GIS) technology, examining its theoretical foundations, key components, and operational principles.

MATERIALS AND METHODS

The range of GIS applications is extensive, encompassing any context in which spatial features must be represented and analyzed. GIS provides the capability to acquire, store, manage, manipulate, and interpret spatially referenced data, as well as to communicate the outcomes of such analyses through thematic cartographic representations.

The adoption of a GIS is typically informed by jurisdictional considerations (e.g., at the level of a municipality), specific objectives, or the requirements of a given application. In practice, GIS implementations are frequently customized to address the particular needs and operational contexts of individual organizations *(Khandve, P., & Mokadam. A.M., 2011).*

GIS can play a crucial role in the analysis and rapid development of intervention strategies for high-risk areas. GIS constitutes a central tool in environmental data management, facilitating data validation, adherence to digital data transfer standards, as well as the collection, dissemination, and analysis of information.

Moreover, GIS serves as a platform for communicating environmental information to both the public and decision-makers, providing the technical foundation for integrating multimedia approaches within the environmental decision-making process.

From the analysis of Figure 2, the main fields of application of GIS technologies in environmental engineering can be highlighted.

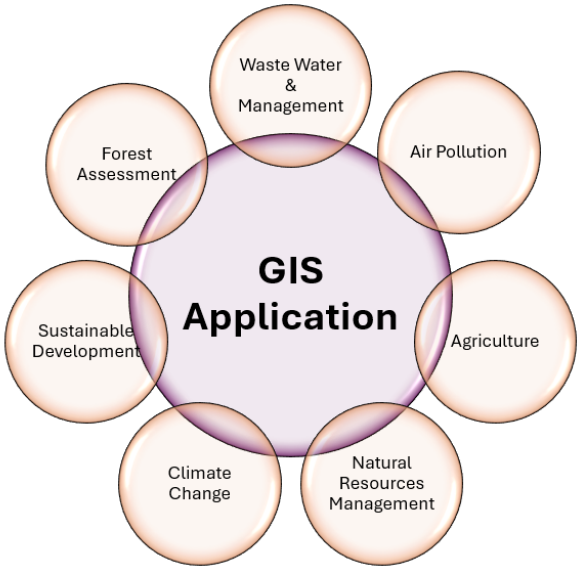

Fig. 2 - Application of GIS for various environmental solutions

RESULTS

GIS has many uses, especially where spatial features need to be created and studied. It helps in collecting, storing, changing, analyzing, and showing information that is connected to a location, and also in sharing the results through special maps. The way a GIS is set up usually depends on the area it covers, like a city, or the goal it serves. Often, a GIS system is made to fit the specific needs of an organization.

Ramroop grouped GIS uses in water resources into these categories: water resources management, watershed management, flood management, groundwater management, water quality, biodiversity and habitat, pollution prevention and control, following rules and regulations, sustainable development, and working with agencies and organizations *(Ramroop, S., 2010).*

Regarding agriculture, GIS and RS (remote sensing) technologies can improve agricultural decisions and policies. They allow for a more efficient analysis of spatial factors that influence productivity, contributing to sustainable agricultural policies and evidence-based interventions. However, in many low- and middle-income countries, the use of GIS is limited due to a lack of reliable spatial data and limited analytical skills *(Tu, L. H.; & Ha, N. T., 2023)*.

This is problematic given the urgent need to modernize agriculture and food production. For optimal use, governments, farmers, and other stakeholders (researchers, consultants, decision-makers, distributors, etc.) must collaborate and have access to up-to-date spatial data.

This information is essential for planning and implementing agricultural policies, as well as for supporting small farmers in their decision-making. GIS and RS have important applications in precision agriculture, crop monitoring, soil fertility management, drought prevention, and disease detection, all of which contribute to food security. To realize this potential, it is necessary to develop comprehensive and up-to-date spatial databases, along with advanced analytical methods capable of providing useful insights for agricultural policies and practices *(Asif, R., 2024).*

Environmental engineering focuses on reducing pollution and finding solutions for managing water, air, and waste. Since environmental issues have a spatial dimension, GIS is essential for collecting and analyzing geographic data. Integrating GIS into environmental engineering allows for modeling phenomena, supports decision-making, and provides tools for protecting the environment.

Through digital maps with layers of information (such as environmental trends, soil stability, pesticide use, pollution sources, etc.), GIS helps researchers and engineers understand and manage the environment more efficiently.

GIS plays a key role in analyzing high-risk environments and in quickly developing mitigation plans. It is a crucial tool for validating, transferring, recovering, and analyzing environmental data. Additionally, GIS helps communicate information to the public and decision-makers, becoming a technical basis for environmental decisions. With the development of spatial standards, the internet, and modern technologies,

environmental information becomes accessible to all users in a relevant spatial context *(Sharma, V.N., Mohammmed, J., & Uppuluri, S., 2009).*

Regarding climate changes, GIS plays a key role in field. It gives scientists, leaders, and local groups the tools and knowledge they need to learn about how the environment is changing. With spatial data, GIS helps people look at and analyze a lot of information, making it easier to spot patterns, trends, and possible impacts.

By placing data like temperature readings, rainfall levels, and plant coverage on maps, GIS helps researchers better understand how climate change is affecting different regions and natural systems (GIS in Climate Change Analysis) *(Le Hoangtu, P. T., 2023).*

Motor vehicles are closely linked to rising air pollution in cities around the world. In addition to releasing large amounts of CO2, these vehicles also emit significant levels of CO, HC, NOx, SPM, and other harmful air pollutants into the atmosphere, which have serious effects on both the environment and human health.

Air quality is crucial for our health and the environment, but it can be hard to track down the exact sources of pollution. GIS technology helps by collecting and organizing data in a way that shows how poor air quality is connected to problems in human and environmental health. This makes it easier to monitor pollutant emissions. With GIS, we can find out where pollutants come from and keep track of those areas to help protect the air we breathe *(Khandve, P., & Mokadam, A.M., 2011).*

CONCLUSIONS

GIS technology is a critical tool in environmental engineering. It integrates and analyzes complex spatial data, helping us better understand natural events and the effects of human activities. GIS aids sustainable decision-making through predictive modeling, real-time monitoring, and identifying vulnerable areas. Its applications include water resource management, pollution control, biodiversity protection, sustainable agriculture, and analyzing climate change.

However, using GIS comes with challenges, especially in places that lack up-to-date databases and analytical skills. Still, its potential to help create effective environmental policies and support societal adaptation to climate change means GIS is more than just a technical tool. It also serves as a key support for environmental protection and sustainable development.

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STONE PAPER AS A SUSTAINABLE ALTERNATIVE: APPLICATIONS, CHALLENGES AND OPPORTUNITIES

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STONE PAPER CA ALTERNATIVĂ SUSTENABILĂ: APLICAȚII, PROVOCĂRI ȘI OPORTUNITĂȚI

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Keywords: *Stone Paper, calcium carbonate, sustainable production*

ABSTRACT

Stone Paper, produced mainly from micronised calcium carbonate derived from recycled marble residuals, offers a sustainable alternative to traditional cellulose-based paper and plastic-based packaging solutions. By utilizing industrial by-products, it reduces deforestation, water consumption, and the environmental impacts of waste disposal. This review explores innovative strategies for integrating recycled marble residuals into Stone Paper production, highlighting its role in promoting resource efficiency and circular economy principles. A comprehensive literature review was conducted to examine manufacturing techniques, environmental benefits, and market adoption. Case studies and life cycle assessments were analyzed to compare Stone Paper with conventional paper. Stone Paper production demonstrates significant potential to valorize residual materials, lower carbon emissions, and conserve water resources. The public–private partenership illustrate the feasibility of large-scale adoption while addressing challenges such as recycling pathways and production scalability. Stone Paper represents a high-performance, eco-friendly material that transforms recycled marble residuals into a valuable resource. Its adoption can mitigate environmental challenges, enhance material efficiency, and support sustainable industrial practices.

REZUMAT

Hârtia din piatră, produsă în principal din carbonat de calciu micronizat, derivat din praf de marmură rezidual, oferă o alternativă sustenabilă la hârtia tradițională pe bază de celuloză, precum și la soluțiile de ambalare pe bază de plastic. Prin utilizarea produselor secundare industriale se reduc defrișările, consumul de apă și impactul asupra mediului cauzat de eliminarea necorespunzătoare a deșeurilor. Această lucrare trece în revistă strategii inovatoare pentru integrarea prafului de marmură rezidual în producția de stone paper, subliniind rolul său în promovarea eficienței utilizării resurselor și a principiilor economiei circulare. A fost realizată o analiză a literaturii de specialitate pentru a examina tehnicile de fabricație, beneficiile de mediu și adoptarea pe piață. Au fost analizate studii de caz și evaluări ale ciclului de viață pentru a compara hârtia din piatră cu produsele convenționale. Producția de hârtie din piatră demonstrează un potențial semnificativ de valorificare a reziduurilor industriale, reducere a emisiilor de carbon și conservare a resurselor de apă. Parteneriatul public–privat ilustrează fezabilitatea adoptării la scară largă, abordând în același timp provocări precum opțiunile de reciclare și scalabilitatea producției. Hârtia din piatră reprezintă un material performant și ecologic care transformă praful de marmură rezidual într-o resursă valoroasă. Adoptarea sa poate atenua provocările de mediu, poate îmbunătăți eficiența materialelor și poate sprijini practicile industriale sustenabile.

INTRODUCTION

Global demand for paper and packaging continues to rise, creating environmental pressures such as deforestation, water scarcity, and plastic pollution (*Kaushani, K. G., Rathnasinghe, N. L., Katuwawila et al, 2022*). Conventional pulp and paper production consumes substantial water and energy and generates chemical effluents (*Hawanis, H. S. N., Ilyas, R. A., Jalil et al, 2024*).

Stone Paper, also known as mineral paper or rock paper, replaces cellulose fibers with finely ground calcium carbonate ($CaCO_3$) and incorporates a polymer binder, typically high-density polyethylene (HDPE)

(*Indriati, L., Nugraha, M. A., & Perng, Y. S.,2020; Swain, N., Saini, P., Bhati et al, 2023*). Commercial formulations are generally ~80% $CaCO_3$ and ~20% HDPE.

This composition imparts water and tear resistance, dimensional stability, and a smooth surface suitable for printing, while altering environmental impacts compared to conventional papers (*Indriati, L., Nugraha, M. A., & Perng, Y. S.,2020; Swain, N., Saini, P., Bhati et al, 2023; Akpolat, C., & Akgül, A., 2024*).

Research methodology surrounding Stone Paper examines its durability, water resistance, and recyclability, showcasing advantages over traditional paper in various applications (*Indriati, L., Nugraha, M. A., & Perng, Y. S.,2020; Swain, N., Saini, P., Bhati et al, 2023*). For instance, studies have demonstrated that Stone Paper can outperform standard paper in durability, positioning it as a viable option for sectors ranging from packaging to education.

This fundamental transition toward using alternative fibers encapsulates a shift toward sustainability that is crucial for the future of material production (*Li, J., Sun, J., Zhang, L et al, 2025, Fathi, Y., Abdulkhani, A., Hamzeh, Y et al 2024*).

This review synthesizes recent literature (technical studies, LCAs, and case reports) on Stone Paper manufacturing, environmental performance, applications, limitations, and policy/market opportunities with a focus on materials derived from recycled marble residuals (an important waste stream in regions with active stone industries).

MATERIALS AND METHODS

A structured literature search was performed in Scopus, Web of Science, Google Scholar and publisher sites (Elsevier, Springer, MDPI, AIP Proceedings). Search terms included: “Stone Paper”, “mineral paper”, “Terraskin”, “calcium carbonate paper”, “life cycle assessment Stone Paper”, “Stone Paper recycling”, and combinations with “marble residuals” and “industrial by-products”. Inclusion criteria prioritized peer-reviewed articles, conference proceedings, and technical LCA reports; manufacturer LCAs and recognized technical reports were used when peer-reviewed LCA studies were sparse.

Where possible, case studies and LCAs comparing Stone Paper to cellulose paper and plastic films were extracted and summarized. Because Stone Paper literature is a mixture of peer-reviewed studies and industry reports, each source type is noted in the reference list and when used in the text.

Stone paper: materials and manufacturing

The exploration of innovative materials has led to the emergence of Stone Paper, a unique product synthesized primarily from calcium carbonate, bounded by a non-toxic polymer (*Indriati, L., Nugraha, M. A., & Perng, Y. S.,2020; Swain, N., Saini, P., Bhati et al, 2023*).

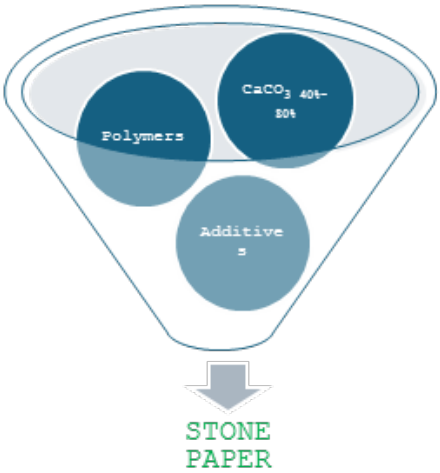

Fig. 1 - The components of Stone Paper

This material is notable for its environmentally friendly production process; the manufacturing of Stone Paper employs no water, no trees, and significantly reduces carbon emissions compared to traditional paper methods.

Multiple studies highlight its superior characteristics, including water resistance, tear durability, and the ability to withstand challenging environmental conditions, which make it a viable alternative for various

applications, from packaging to stationery (*Indriati, L., Nugraha, M. A., & Perng, Y. S.,2020; Swain, N., Saini, P., Bhati et al, 2023*).

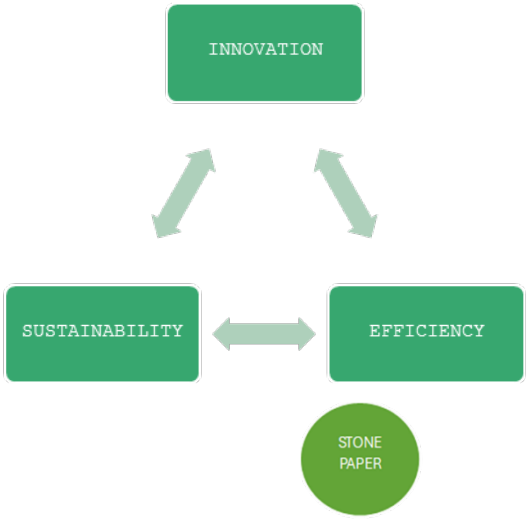

Fig. 2 - The values of Stone Paper

Furthermore, researchers have employed methodologies that assess the life cycle of Stone Paper, revealing a less detrimental impact on ecosystems compared to conventional papers (citing its ability to reduce deforestation and energy consumption) *(Affeldt, C., Leung, A., & Yang, K., 2016).* The versatility and sustainability of Stone Paper underline its potential as a transformative material in the context of increasing environmental awareness and the necessity for sustainable solutions *(Swain, N., Saini, P., Bhati et al, 2023).*

A typical industrial process includes: collection and preparation of stone residuals → micronization (ultrafine grinding to produce $CaCO_3$ powder) → mixing with binder and additives → extrusion and calendaring to form sheets → surface finishing for printability and coating as required (Figure 3).

The production avoids conventional digestion, pulping and bleaching steps used in cellulose paper mills, significantly reducing process water demand *(Hawanis, H. S. N., Ilyas, R. A., Jalil, R et al, 2024).*

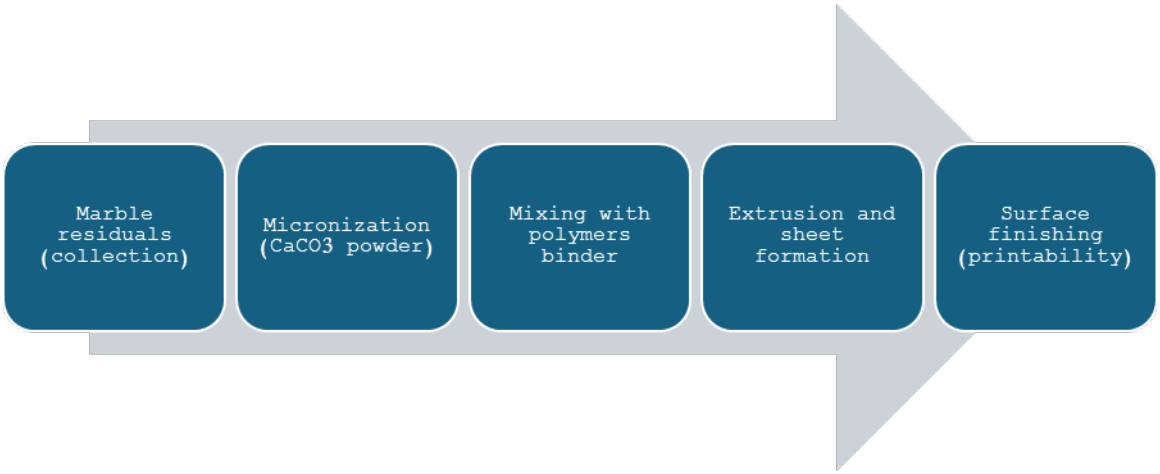

Fig. 3 - Industrial production process for Stone Paper

Environmental performance (lca insights)

As the pursuit of sustainable alternatives intensifies, innovative materials like Stone Paper present significant potential to lessen ecological footprints associated with traditional paper production. Traditional paper relies heavily on wood pulp, consuming vast quantities of water, energy, and chemicals, leading to deforestation and habitat destruction (*Swain, N., Saini, P., Bhati et al, 2023, Affeldt, C., Leung, A., & Yang, K., 2016*). In contrast, Stone Paper is composed primarily of calcium carbonate, using far less water and no trees, which minimizes biodiversity loss and reduces greenhouse gas emissions (*Fathi, Y., Abdulkhani, A., Hamzeh, Y et al, 2024*).

One of the most consistent advantages reported for Stone Paper is drastically lower process water use relative to conventional wood-pulp paper production — the stone-based process typically requires

negligible process water, since pulping/bleaching stages (which consume the bulk of water in conventional paper) are absent. This outcome is emphasized in technical and industry LCA summaries *(Swain, N., Saini, P., Bhati et al, 2023, Affeldt, C., Leung, A., & Yang, K., 2016).*

Results for greenhouse gas (GHG) emissions and primary energy vary by study and depend on the polymer source, electricity grid, and whether $CaCO_3$ feedstock is from quarrying or recycled marble residuals (*Ippolito, F., Hübner, G., Claypole, T et al, 2021, Bilir, T., Karadağ, Ö., & Aygün, B. F., 2022*).

Some LCAs indicate Stone Paper can reduce certain impact categories compared to coated papers and some plastic films, while others point out that the polymer binder (HDPE) and crushing/grinding energy can increase fossil-based impacts if not managed. Thus, LCA outcomes are context-dependent: processing technology, binder selection, electricity mix and end-of-life scenarios strongly influence results (*Swain, N., Saini, P., Bhati et al, 2023, Affeldt, C., Leung, A., & Yang, K., 2016*).

Traditional pulp bleaching can generate chlorinated phenolics and other toxic effluents (e.g., studies on chlorophenolic compounds from wheat straw pulp bleaching) (*Indriati, L., Nugraha, M. A., & Perng, Y. S., 2020*).

Stone Paper avoids those bleaching effluents but introduces considerations related to microplastic shedding, additive residues, and potential release of particles if sheets degrade. Comparative risk profiles therefore differ rather than uniformly “improve” across all endpoints (*Indriati, L., Nugraha, M. A., & Perng, Y. S., 2020*).

Stone Paper is recyclable in principle: it can be treated as a plastic-rich stream and processed using appropriate polymer-recycling pathways (separation, re-extrusion), or in some cases collected for recovery into composite products (*Swain, N., Saini, P., Bhati et al, 2023*).

However, in practice, Stone Paper is often misidentified as cellulose paper in mixed paper collection streams, leading to contamination issues and limited recycling. Where dedicated collection streams exist, producers and recyclers report good recovery rates, but infrastructure is the bottleneck.

Applications

The exploration of innovative materials has yielded significant insights into the practical applications of Stone Paper, particularly in various industries seeking sustainable alternatives. Research methodology often involves comparative analyses with traditional papers, highlighting characteristics such as superior water resistance, durability, and the absence of wood pulp (*Indriati, L., Nugraha, M. A., & Perng, Y. S.,2020; Swain, N., Saini, P., Bhati et al, 2023*).

By employing experimental frameworks similar to those detailed in which examines structural resilience of materials under stress, scholars can assess Stone Papers capacity to withstand harsh environmental conditions. For instance, studies have demonstrated its potential in packaging, where its moisture-resistant properties enhance product longevity and reduce waste (*Liendo, F., Arduino, M., Deorsola, F. A et al, 2022; Li, J., Sun, J., Zhang, L., Gao, C et al, 2025*).

Furthermore, the application of stone paper in educational contexts, such as notebooks and writing materials, showcases its feasible transition from concept to market. This suite of applications elucidates not only the versatility of Stone Paper but also its alignment with contemporary sustainability goals, affirming its role as a pivotal material in the ongoing quest for eco-friendly solutions (*Indriati, L., Nugraha, M. A., & Perng, Y. S.,2020; Swain, N., Saini, P., Bhati et al, 2023*).

The exploration of packaging methodologies reveals significant potential for integrating Stone Paper into various consumer products. Stone Paper, characterized by its durability, water resistance, and decreased reliance on trees, presents an alternative to traditional packaging materials.

Research indicates that effective packaging strategies can enhance sustainability by addressing the complexities of material choice and resource interdependencies within supply chains *(Kaushani, K. G., Rathnasinghe, N. L., Katuwawila, N et al, 2022*).

For example, studies on wine labels have highlighted the competitive appeal of alternative substrates, yet they also underscore challenges in fully integrating stone paper into existing frameworks where it may not outperform conventional materials in specific physical properties (*Affeldt, C., Leung, A., & Yang, K., 2016*).

This duality of opportunity and limitation emphasizes the necessity for further research in developing tailored specifications that can elevate stone papers viability in packaging applications, ultimately contributing to more sustainable consumer practices while navigating the embedded resource complexities inherent in e-commerce.

In assessing the impact of Stone Paper on educational materials and stationery, it is crucial to consider its unique characteristics that promote sustainability. Unlike traditional paper made from trees, stone paper is derived from calcium carbonate, offering a water permeable quality that enhances durability and resistance to tearing and wet conditions. This resilience makes it an ideal medium for educational tools such as notepads, textbooks and art supplies (*Indriati, L., Nugraha, M. A., & Perng, Y. S., 2020; Swain, N., Saini, P., Bhati et al, 2023*).

Challenges and limitations

The dominant practical obstacle is end-of-life management: Stone Paper often requires either recognition and routing into plastic recycling streams, or dedicated mono-streams. Because municipal collection systems are typically optimized for paper vs. plastic separation, widespread adoption requires adjustments to collection, labeling and public guidance. Where dedicated recycling streams exist, stone paper recycling can be efficient; where not, contamination and landfill remain likely. Even though $CaCO_3$ replaces cellulose, the binder is often fossil-based HDPE. This creates tradeoffs in GHG and fossil resource impacts unless the polymer is bio-sourced or recycled.

Research into bio-polymers and lower binder fractions is ongoing. The complexity of contemporary research is underscored by the necessity for interdisciplinary collaboration, particularly in fields such as sustainability, which includes innovative materials like Stone Paper.

Researchers often grapple with navigating differing institutional logics, which encompass varied goals such as societal impact, commercial viability, and the generation of academic knowledge. This divergence can inhibit effective collaboration, thereby slowing progress in addressing critical issues (*Indriati, L., Nugraha, M. A., & Perng, Y. S., 2020; Swain, N., Saini, P., Bhati et al, 2023*).

Stone Paper may face higher production costs (micronization energy, specialized extrusion) depending on scale and local supply. Market acceptance and willingness-to-pay for sustainable alternatives are also a factor; policy incentives and procurement standards may accelerate adoption. Hibiki & Managi's work on information provision and market incentives (PRTR systems) suggests that better environmental disclosure and market signals can influence firm choices and could be leveraged to support materials like Stone Paper (*Hibiki, A., & Managi, S., 2010*).

Opportunities and future research

One of the most promising avenues to improve Stone Paper sustainability is the development of bio-based or degradable binders to replace conventional fossil-based polymers. By substituting with bio-binders derived from renewable sources, the environmental footprint of Stone Paper can be significantly reduced, particularly regarding fossil fuel consumption and end-of-life disposal challenges. Such bio-binders could also enhance biodegradability, enabling Stone Paper to be incorporated into composting or organic waste streams where feasible, thus advancing circular economy objectives (*Swain, N., Saini, P., Bhati et al, 2023*).

Industrial symbiosis represents another opportunity to increase the sustainability of Stone Paper production. Regions with active stone, marble, or mining industries can valorize mineral residuals locally, using them as a source of calcium carbonate for paper production. This approach reduces the need for long-distance transport of raw materials, lowers associated greenhouse gas emissions, and creates closed-loop material supply chains that integrate existing industrial waste streams into the Stone Paper value chain.

As the urgency for sustainable materials intensifies, the research trajectory for Stone Paper must adapt to emerging ecological challenges and technological advancements. Future investigations could delve into material properties such as biodegradability and the recycling potential of Stone Paper, particularly in comparison to traditional alternatives. This could involve experimental studies that evaluate the environmental impact of stone paper throughout its lifecycle.

CONCLUSIONS

Stone Paper — produced mainly from micronized $CaCO_3$ and a polymer binder — is an emerging, high-performance, and potentially more resource-efficient alternative to conventional cellulose paper for many applications. Its main environmental strengths are near-zero process water use and the potential to valorize marble residuals, while its principal limitations are related to polymer dependence and end-of-life infrastructure. To realize the full environmental benefits, efforts must focus on binder innovation, transparent LCA reporting, and the development of dedicated recycling streams (public-private partnerships

and procurement incentives will speed adoption). With coordinated technical and policy actions, Stone Paper can take an important role in sustainable material portfolios.

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ADSORPTION EFFICIENCY OF COOPER FROM WASTEWATER BY USE SOME ALTERNATIVE ADSORBENT MATERIALS

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EFICIENȚA DE ADSORBȚIE A CUPRULUI DIN APE UZATE PRIN UTILIZAREA UNOR MATERIALE ADSORBANTE ALTERNATIVE

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Keywords: *adsorption, adsorbent materials, copper ions, wastewater*

ABSTRACT

The removal of heavy metals is an important aspect in wastewater treatment. This is achieved, in particular, through the adsorption process, using activated carbon as an adsorbent material. Since activated carbon is a rather expensive material, some research has been focused on finding and developing adsorbent materials from industrial and agricultural waste, which are cheap, available and in large quantities. In this work, four such adsorbent materials were used, namely blast furnace slag, walnut shells, hazelnut shells, sawdust, to monitor the efficiency of removing copper ions from wastewater. It was observed, following laboratory experiments, a high efficiency of removing copper ions in the case of the adsorbent materials studied, from 21.66%, in the case of sawdust, to 99.96%, in the case of blast furnace slag. The aim of this work is to deepen the discovery of alternative adsorbent materials, derived from industrial and agricultural waste, to remove heavy metals, in this case copper ions, from wastewater.

REZUMAT

Eliminarea metalelor grele este un aspect important în epurarea apelor uzate. Acest lucru se realizează, în special, prin procesul de adsorbție, utilizând ca material adsorbant cărbunele activ. Întrucât cărbunele activ este un material destul de scump, unele cercetări s-au orientat spre găsirea și dezvoltarea unor materiale adsorbante provenite din deșeurile industriale și agricole, care sunt ieftine, disponibile și în cantitate mare. În această lucrare s-au utilizat patru astfel de materiale adsorbante, și anume zgură de furnal, coji de nucă, coji alune de pădure, rumeguș, pentru a urmări eficiența de îndepărtare a ionilor de cupru din apele uzate. S-a observat, în urma experimentelor de laborator, o eficiență de îndepărtare a ionilor de cupru ridicată în cazul materialelor adsorbante studiate, de la 21,66%, în cazul rumegușului, până la 99,96%, în cazul zgurii de furnal. Scopul acestei lucrări este de a aprofunda descoperirea unor materiale adsorbante alternative, provenite din deșeurile industriale și agricole, pentru a îndepărta metalele grele, în acest caz ionii de cupru, din apele uzate.

INTRODUCTION

Water is a vital resource for sustaining life and for this reason water quality must be protected and maintained in parameters as close as possible to natural ones. The existence of wastewater, resulting from the use of water in various anthropogenic processes, has led to the development of processes for eliminating pollutants from this wastewater. Heavy metals are some of the strongest water pollutants because they are chemical elements with a high toxicity in small quantities. In this work, the efficiency of copper removal from wastewater by adsorption was investigated, using various materials derived from industrial and agricultural waste.

Adsorption is one of the most widely used methods for wastewater treatment, as it presents multiple advantages, such as simplicity of use, simple implementation, use of a variety of substances as adsorbents, which leads to a high efficiency of the purification process (*Senthil Rathia, B. et al., 2024*).

. Activated carbon is the most well-known and used adsorbent material in the adsorption process, but, since it is a rather expensive material (*Mishra, P.C. et al., 2009*), the use of alternative materials derived from various types of waste (*Wang, Z. et al., 2016*) has been pursued, such as blast furnace slag (*Dong, Q.G. et al., 2024*), hazelnut shells, walnut shells (*Rawlins, C.H. et al., 2017*), sawdust (*Majid, H. et al., 2022*). Considering the major concern related to the toxicity of heavy metals, as well as the existence of strict

requirements regarding the removal of heavy metals from wastewater, it is necessary to develop adsorption materials that are efficient and economical (*Covaliu, C. et al., 2014*).

To observe the efficiency of removing heavy metals from wastewater using alternative adsorbent materials, a laboratory experiment was conducted to investigate the possibility of the four materials listed above to be used in the adsorption of copper ions. Copper is a heavy metal with a density of 8.96 g/cm^3, a good conductor of heat and electricity, originating from various sources such as metal manufacturing, chemical manufacturing, steel industry, fertilizers and pesticides. It is necessary to remove copper ions from wastewater, as too high a copper content can have undesirable effects on human health, such as anemia, hair loss, kidney problems, headaches (*Senthil Rathia, B. et al., 2024*).

MATERIALS AND METHODS

The adsorbent materials, derived from industrial and agricultural waste, used to test the removal of copper ions from wastewater were blast furnace slag, walnut shells, hazelnut shells, and sawdust. The samples from the four materials used were dried, crushed, ground and sieved through a set of filters to obtain a sample size of 45 µm.

This is because adsorption is the purification process based on the phenomenon of retention on the surface of a body of molecules of a substance dissolved in water, and it is desirable that the granulation of the adsorbent materials be as small as possible in order to have a larger contact surface.

Adsorption experiments were performed using a multi-element solution of heavy metals to obtain wastewater samples. Samples of slag, walnut shells, hazelnut shells, sawdust, with a particle size of 45 µm, in quantities of 10 mg, 25 mg and 50 mg were immersed in 30 mL of heavy metal solution with a concentration of 5 mg/L. Magnetic stir plates were used for homogenization, at 60 rpm, for 60 minutes. All experiments were performed at room temperature.

To determine the concentration of copper ions, a contrAA 800 atomic absorption spectrophotometer was used, where the sample solution to be analyzed is sprayed into the flame, taking place a series of processes through which free atoms are obtained. The analytical characteristics by which the analysis of copper ions was performed, using an atomic absorption spectrophotometer, are specified in the table below (Table 1).

Table 1

Analytical characteristics of the determination of copper ions

Analytical characteristics / Heavy metals	Wavelength (nm)	Linear regression	Detection limit (mg/L)	Limit of quantification (mg/L)	Flame type
Cu^{2+}	324.754	y=0.0187+0.0954x R^2=0.9941	0.0093	0.0280	acetilenă - aer

The Cu^{2+} removal efficiency from wastewater of the four materials studied was calculated as follows:

$$\textit{Removal efficiency, (\%)} = \frac{C_i - C_t}{C_i} \cdot 100 \quad (1)$$

where:

Ci (mg/L) is the initial concentration, and

Ct is the total concentration at a given time, of the Cu^{2+}

RESULTS

All experiments were performed three times, and the average data were used in data analysis. Following examination of 10 mg, 25 mg and 50 mg samples with the contrAA 800 atomic absorption spectrophotometer, the following amounts of Cu^{2+} were found (Table 2):

Table 2

Amounts of Cu^{2+} found in the analyzed samples

Adsorbent material	Heavy metal	Contact time (minutes)	Concentration (mg/L)		
			10 mg	25 mg	50 mg
Blast furnace slag	Cu^{2+}	60	0,0048	0,0023	0,0002
Walnut shells			0,2110	0,2127	0,2425
Hazelnut shells			0,1812	0,1988	0,3021

Sawdust	0,2221	0,3870	0,3917

The efficiency of removing copper ions from wastewater, using the adsorbent materials taken into work, was evaluated as follows (Table 3):

Table 3

The efficiency of removing copper ions from wastewater

Adsorbent material	Heavy metal	Contact time (minutes)	Removal efficiency (%)		
			10 mg	25 mg	50 mg
Blast furnace slag	Cu^{2+}	60	99,04	99,54	99,96
Walnut shells			57,80	57,46	51,50
Hazelnut shells			63,76	60,24	39,58
Sawdust			55,58	22,60	21,66

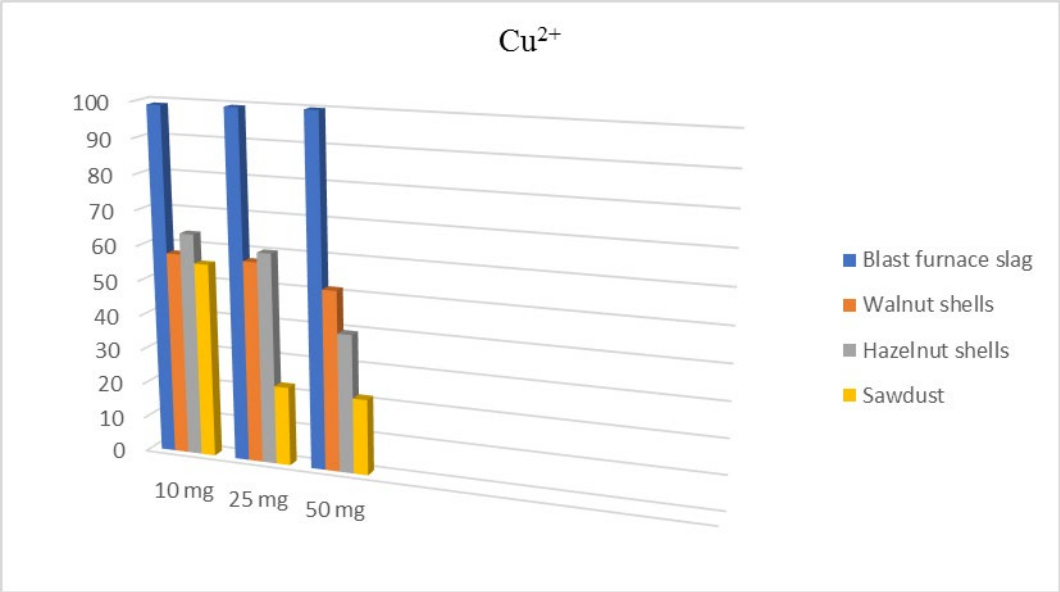

Fig. 1 - Copper ion adsorption efficiency by adsorbent materials

As can be seen from Figure 1, the highest value of the copper ion removal efficiency from the wastewater sample was obtained in the case of blast furnace slag, and the lowest removal efficiency value was obtained in the case of sawdust. Thus, in the case of a quantity of 50 mg of blast furnace slag, the copper ion removal efficiency was 99.96%, for 25 mg of blast furnace slag, the efficiency was 99.54%, and for the quantity of 10 mg there was a removal efficiency of 99.04%.

For hazelnut shells, a removal efficiency of 63.76%, 60.24% and 39.58% was obtained for the quantities of 10 mg, 25 mg and 50 mg of hazelnut shells. In the case of walnut shells, there was an efficiency of 57.80%, 57.46%, 51.50% for the amounts of 10 mg, 25 mg and 50 mg of walnut shells, and by using sawdust as an adsorbent material, a removal efficiency of 55.58%, 22.60%, 21.66% was obtained for the same amounts of 10 mg, 25 mg and 50 mg.

The contact time between adsorbent and adsorbate was 60 minutes for each adsorbent material used.

The amount of adsorbent material used influenced the efficiency of removing copper ions from the wastewater sample. Thus, the best efficiency was for a quantity of 50 mg, in the case of blast furnace slag 99.96%, respectively a quantity of 10 mg, in the case of walnut shells 57.80%, hazelnut shells 63.76 and sawdust 55.58%.

The lowest removal efficiency, for each adsorbent material used, was for the amount of 50 mg, in the case of sawdust 21.66%, hazelnut shells 39.58% and walnut shells 51.50%, and for the amount of 10 mg, in the case of blast furnace slag 99.04%. As can be seen, blast furnace slag, in the case of each amount of adsorbent material, i.e. 10 mg, 25 mg and 50 mg, had a high copper ion removal efficiency, i.e. 99.04%, 99.54% and 99.96%.

The high efficiency of copper removal, using blast furnace slag as an adsorbent material, can be explained by the possibility of copper to form alloys with silicon, calcium, zinc, sulfur, etc. elements that are found in the composition of blast furnace slag.

CONCLUSIONS

Adsorbent materials derived from industrial and agricultural waste offer a reliable and efficient alternative in wastewater treatment. Following laboratory testing, a high efficiency of the adsorbent materials used, namely blast furnace slag, walnut shells, hazelnut shells and sawdust, was observed in the removal of copper ions from wastewater.

These adsorbent materials were used at a fine granulation of 45 μm, because in order to have a large contact surface between the adsorbent and the adsorbate, the granulation of the adsorbent materials must be as small as possible.

The most efficient adsorbent material for copper ions was blast furnace slag, and the adsorbent material with the lowest removal efficiency was sawdust. Thus, in the case of blast furnace slag, in an amount of 50 mg, the removal efficiency was 99.96%, and sawdust, in an amount of 50 mg, presented a removal efficiency of 21.66%.

A promising result, in terms of the removal of copper ions from wastewater, was also obtained in the case of walnut shell, in an amount of 10 mg, an efficiency of 57.80%, respectively, in the case of hazelnut shell, in an amount of 10 mg, an efficiency of 63.76%.

This aspect indicates the possibility and necessity of using such adsorbent materials, derived from industrial and agricultural waste, in wastewater treatment, as they are accessible, cheap and efficient and, at the same time, reduce the amount of waste that may occur.

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EXPERIMENTAL STUDY ON THE DYNAMIC BEHAVIOR OF THE 3SLP SPRINGBOARD IN RUNNING TESTS

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STUDIU EXPERIMENTAL PRIVIND COMPORTAMENTUL DINAMIC AL TRAMBULINEI 3SLP ÎN TESTELE DE ALERGARE

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***Keywords**: springboard, dynamic behavior, gymnastics equipment, impact testing, elasticity*

ABSTRACT

Gymnastics, as a complex and highly educational sport, plays a central role in both physical development and elite athlete training. The quality and safety of gymnastics equipment are critical factors in achieving optimal performance and preventing injuries in schools and sports clubs. Among various apparatuses, the springboard (or vaulting board) serves as a key technical component, converting the athlete's kinetic energy into vertical and horizontal momentum essential for proper acrobatic execution. Its performance depends directly on elastic properties and component reliability, influencing both movement execution and user safety.Specialized studies indicate that optimal springboard elasticity is not an absolute parameter but rather a balance between frame stiffness, elastic element characteristics (coil springs, leaf springs), and assembly. Reliability—defined as durability and consistent performance—depends on the elastic system's behavior under repeated and varied loads.This study experimentally evaluates the dynamic behavior of a 3SLP springboard through controlled tests involving three participants with different body masses (40 kg, 58.5 kg, and 68 kg). Tests included controlled drops from heights of 30 cm and 60 cm at specified impact points, as well as running approaches from a 5 m distance. The results highlight the relationship between impact conditions, elastic response, and performance consistency, providing insights for equipment optimization and safety standards in gymnastics training.

REZUMAT

Gimnastica, ca sport complex și extrem de educativ, joacă un rol central atât în dezvoltarea fizică, cât și în antrenamentul sportivilor de elită.Calitatea și siguranța echipamentului de gimnastică sunt factori critici în obținerea performanței optime și prevenirea accidentărilor în școli și cluburi sportive. Printre diversele aparate, trambulina(sau placa de sărituri) servește drept componentă tehnică cheie, transformând energia cinetică a sportivului în impuls vertical și orizontal, esențial pentru o execuție acrobatică corectă.Performanța sa depinde direct de proprietățile elastice și de fiabilitatea componentelor, influențând atât execuția mișcării, cât și siguranța utilizatorului. Studiile specializate indică faptul că elasticitatea optimă a unei trambuline nu este un parametru absolut, ci mai degrabă un echilibru între rigiditatea cadrului, caracteristicile elementelor elastice (arcuri elicoidale, arcuri lamelare)și asamblare.Fiabilitatea definită ca durabilitate și performanță constantă - depinde de comportamentul sistemului elastic sub sarcini repetate și variate.Acest studiu evaluează experimental comportamentul dinamic al unei trambuline 3SLP prin teste controlate care au implicat trei participanți cu mase corporale diferite (40 kg, 58,5 kg și 68 kg). Testele au inclus căderi controlate de la înălțimi0 de 30 cm și 60 cm în puncte de impact specificate, precum și abordări de alergare de la o distanță de 5 m.Rezultatele evidențiază relația dintre condițiile de impact, răspunsul elastic și consecvența performanței, oferind informații pentru optimizarea echipamentului și standardele de siguranță în antrenamentul de gimnastică.

INTRODUCTION

Dimensions and characteristics of the trampoline used in the determinations

The trampoline analyzed in the experiments was made of curved laminated plywood, a material chosen for its robustness and optimal elasticity, capable of ensuring both mechanical resistance and the flexibility necessary for dynamic behavior. The contact surface is upholstered with a layer of polyethylene

and covered with carpet, which improves comfort and increases grip during jumps, reducing the risk of slipping and contributing to the safety of the user. The elastic system is made up of spiral springs made of nickel-plated steel, arranged in such a way as to ensure controlled deformability of the assembly. These include two types of coils:

- a conical spring, consisting of 6 turns, with a total length of 137 mm, an upper diameter of 52.5 mm, a lower diameter of 85 mm and a material thickness of 5.9 mm;
- a cylindrical spring, with 4 turns, with a thickness of 6 mm, a diameter of 65 mm and a total length of 78 mm.

The upper plate of the assembly has a thickness of 16.5 mm, while the lower plate has a thickness of 26.5 mm, both having a width of 142.8 mm. Additional elasticity is provided by a metal slat with a thickness of 5 mm, a width of 50 mm and a length of 595 mm, which reinforces the structure

The overall dimensions of the trampoline are 1200 × 600 × 200 mm (length × width × height), with a front threshold of 20 mm and an extension of 600 mm.

The constructive curves of the plates were defined as follows: the lower lamella has a curvature of 50 mm, and the upper threshold also has a curvature of 50 mm. Through these characteristics, the trampoline offers an optimal combination of rigidity and flexibility, ensuring an elastic behavior suitable for experimental tests on the absorption and redistribution of kinetic energy.

MATERIALS AND METHODS

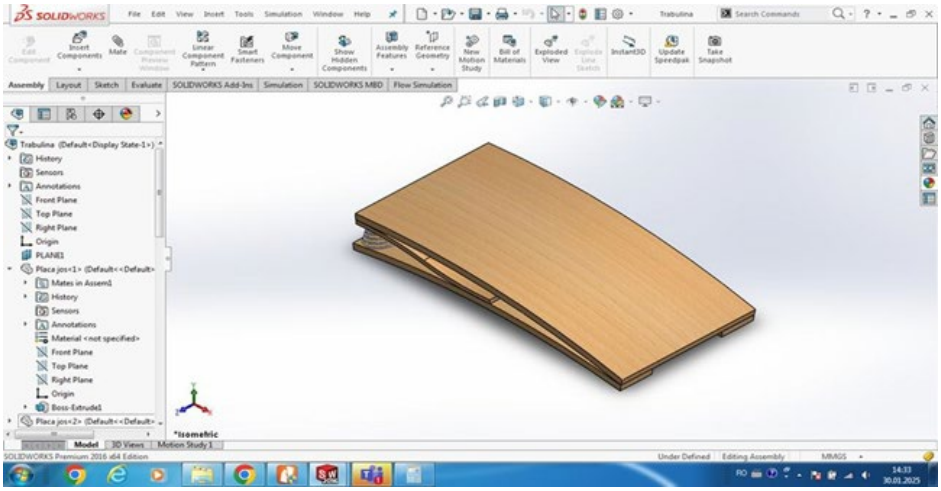

Fig. 1 - Three-dimensional model of the 3SLP trampoline-type elastic structure made in SolidWorks

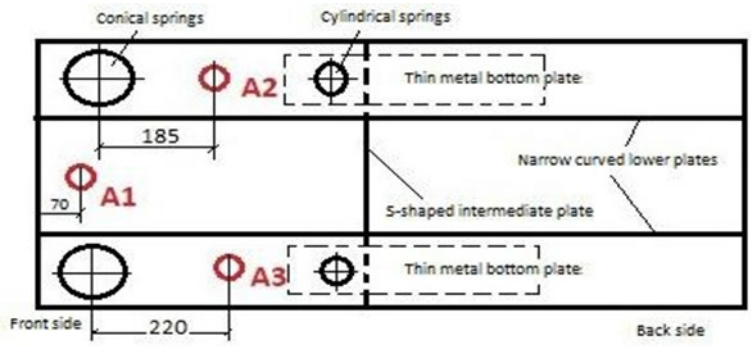

Fig. 2 - Mounting of accelerometers and configuration of the acquisition system

To perform dynamic measurements, three metal plates were fixed on the lower part of the 3SLP elastic structure, acting as supports for the piezoelectric accelerometers. The recordings were made with CCLD sensors, model 4507-B-001 with integrated TEDS, characterized by a sensitivity of 10 mV/g (equivalent to 1 mV/(m s²), a frequency range of 0.1–6000 Hz and a working temperature range between −54 °C and +121 °C, parameters that make them suitable for precision vibration measurements.

The arrangement of the sensors was chosen to capture the differentiated behavior of the structure depending on the monitored area:A1 – located under the front of the upper plate curved in "S", corresponding to position P1, responsible for the direct interaction with the conical springs (*Di Rocco, F., Papale, O., Festino, E., De Maio, M., Cortis, C., & Fusco, A. (2023).*

A2 – positioned in the middle area, on the lower part of the curved plates, at the transition between the truncated conical and cylindrical springs;A3 – installed in the rear part (P3), where the structural response is dominated by the cylindrical springs.

The accelerometers were connected to an NI USB-9233 acquisition system, designed for vibration and noise analysis, and the data were processed using dBFA Suite 4.8.1 software (01dB-METRAVIB, Areva Group), which allowed the recording, integration and visualization of dynamic signals.

RESULTS

To obtain the kinematic parameters, the raw data were subjected to a first-order numerical integration, to determine the instantaneous velocities, and a second- order integration, to calculate the displacements of the measured points *(Eager, D., Zhou, S., Ishac, K., Hossain, I., Richards, A., & Sharwood, L. N. (2022*).

The acquisition system was activated a few seconds before contact, so that the resulting graphs include both the natural oscillations of the structure before impact (of higher frequency) and their modification at the moment of contact, when the amplitudes increase considerably.

The present study analyzes the recordings provided by accelerometers mounted on a 3SLP trampoline, used by a subject with a mass of 40 kg. The main objective is to characterize the elastic behavior of the structure under variable dynamic conditions, which correspond to jumps performed after a 3 m and 5 m run, respectively, within three successive tests (Tests 1, 2 and 3).The data collected by accelerometers A1 and A2 allow the investigation of both the impact zone itself and the way in which the oscillations propagate in the trampoline structure.

Accelerometer A1, located in the frontal area (P1), provides direct information on the local response of the truncated conical springs, while accelerometer A2, positioned in the medial area (P2), captures the combined effects of the two types of springs and the elastic transition phenomenon.

The comparison of the signals recorded in the two positions highlights significant differences in the amplitude and phase of the oscillations suggesting a progressive attenuation of the energy as it propagates from the impact point to the rest of the structure. These results contribute to a more detailed understanding of the distribution of stresses and the role of each elastic zone in the process of absorption and restitution of kinetic energy.

Description of the experimental procedure

To evaluate the dynamic behavior of the structure, tests were carried out with the participation of three volunteer students, with different body masses (40 kg, 58.5 kg and 68 kg). They were subjected to tests consisting of:

- controlled falls from heights of 30 cm and 60 cm, at predetermined impact points (previous figure);
- lunge jumps, after 5 m runs.

The recorded data allowed the analysis of the acceleration evolution in the three measurement positions (A1, A2, A3). For the present study, the results obtained for the 40 kg subject, who performed jumps after 3 m and 5 m runs, within three successive repetitions (Trials 1–3), are presented in particular. The A1 accelerometer, located frontally (P1), provided relevant information regarding the local response of the conical springs, while the A2 accelerometer, positioned medially (P2), recorded the combined effects of the conical and cylindrical springs, highlighting the elastic transition zone *(Križaj, D., & Čuk, I. (2015).*

The comparison of the signals measured in the two positions revealed significant differences in amplitude and phase, which confirms a progressive attenuation of the energy as it propagates from the point of impact to the rest of the structure. These results contribute to a deeper understanding of how the dynamic load is distributed and of the specific role of each elastic zone in the absorption and return of kinetic energy *(Kobayashi, S., & Hasegawa, T. (2021).*

To ensure the full capture of the dynamic phenomenon, the acquisition system was activated a few seconds before the moment of the ball's release.

Thus, in the resulting graphs, relatively high-frequency initial oscillations are observed, associated with the structure's own vibrations before impact.At the moment of contact, these oscillations significantly change their character, becoming more frequent and with a higher amplitude. The first pronounced oscillation in this new regime corresponds to the actual moment of impact between the ball and the trampoline surface.

In this study, the recordings obtained from accelerometers mounted on a 3SLP trampoline, used by a subject with a mass of 40 kg, are analyzed. The main objective is to characterize the elastic behavior of the structure under various dynamic conditions, corresponding to jumps performed after a 3 m and, respectively, 5 m run, within three successive tests (Tests 1, 2 and 3).

The data provided by accelerometers A1 and A2 allow the investigation of both the actual impact zone and the way in which the oscillations propagate in the trampoline structure. Accelerometer A1, located in the frontal area (P1), provides direct information on the local response of the truncated conical springs, while accelerometer A2, positioned in the medial area (P2), captures the combined effects of the two types of springs and the elastic transition phenomenon.

Comparison of the signals recorded at the two positions highlights significant differences in the amplitude and phase of the oscillations, suggesting a progressive attenuation of the energy as it propagates from the point of impact to the rest of the structure. These results contribute to a better understanding of the stress distribution and the role of each elastic zone in the absorption and return of kinetic energy.

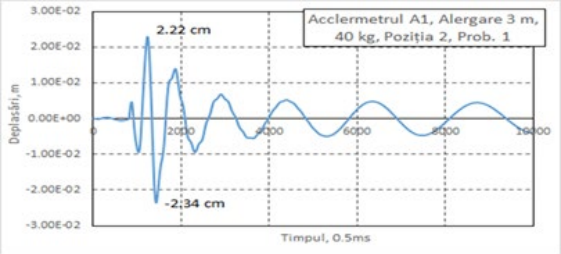

Fig. 3 - Accelerometer A1

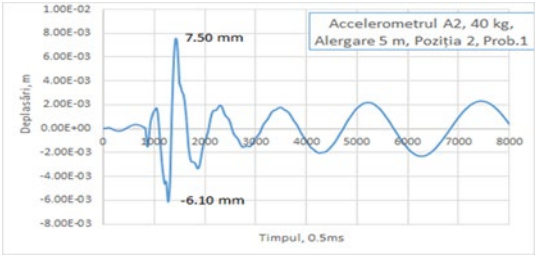

Fig. 4 - Accelerometer A2

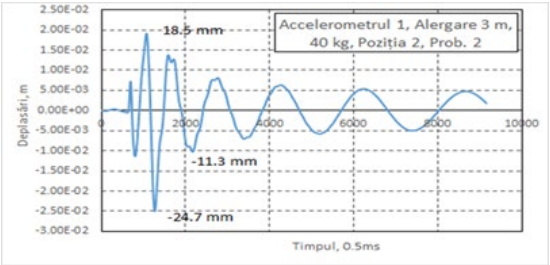

Fig. 5 - Accelerometer A1

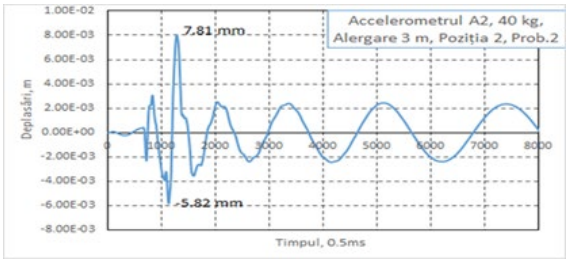

Fig. 6 - Accelerometer A2

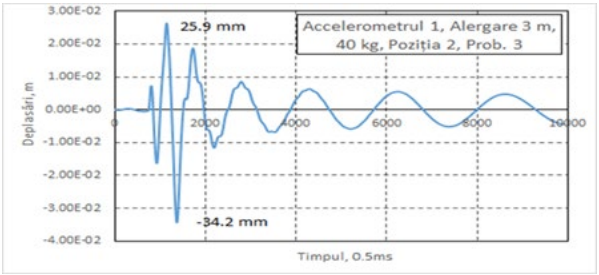

Fig. 7 - Accelerometer A1

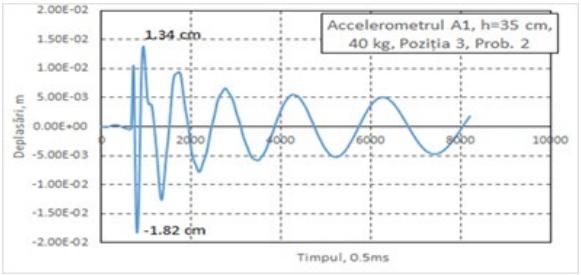

Fig. 8 - Accelerometer A2

Experimental results and interpretationAccelerometer A1 response – 3 m run, subject 40 kg, position P2, sample 1The graph in figure 3 illustrates the response of accelerometer A1 recorded after a jump performed after a 3 m run, by a subject with a mass of 40 kg. The maximum displacements obtained, of +2.22 cm and −2.34 cm, highlight a pronounced and almost symmetrical dynamic behavior with respect to the equilibrium position.

The temporal evolution of the signal shows a progressive decrease in amplitude, which confirms the existence of an efficient damping mechanism in the frontal area. The regular shape of the waves suggests a

rapid and controlled elastic return, and the proximity of the positive and negative extreme values indicates a uniform application of force in the impact area. These characteristics confirm the ability of the frontal plate to take over and redistribute kinetic energy in a balanced way.

Accelerometer A2 response – 5 m run, subject 40 kg, position P2, sample 1.

The graph in figure 4 shows the displacements recorded by the accelerometer A2, located in the median zone, for a jump performed after a 5 m run. The maximum measured values, of +7.50 mm and −6.10 mm, reflect a relatively moderate response of the structure in this zone, despite the higher kinetic energy associated with running over a longer distance. This finding suggests that the P2 position benefits from a higher stiffness or a more efficient constructive support, which limits the amplitude of the deformations. The oscillations are clear, regular and present a visible damping, indicating a predictable and stable elastic behavior. The persistence of the waveform throughout the measurement interval confirms the role of the median zone in dissipating energy without generating local resonance phenomena.

Accelerometer A1 response – 3 m run, subject 40 kg, position P2, sample 2In this experimental repetition, the maximum amplitudes reached +18.5 mm and −24.7 mm, significantly higher than in the previous sample. The difference between the positive and negative displacements suggests an asymmetric impact, most likely determined by a lateral landing of the subject. The initial oscillations are characterized by high amplitudes, and their decrease is relatively slow, which indicates a weaker energy dissipation. This finding confirms the increased sensitivity of the frontal area to the variations in the subject's positioning on the surface. Compared to the tests performed under symmetric impact conditions, sample 2 highlights the importance of load distribution in the overall behavior of the structure *(Lehmann, T., Schleichardt, A., Naundorf, F., & Knoll, K. (2017).*

Accelerometer A2 response – 3 m run, subject 40 kg, position P2, test 2In this test, accelerometer A2 recorded maximum values of +7.81 mm and −5.82 mm, considerably lower than those obtained by A1 under similar conditions. The relatively small difference between the extremes suggests a more uniform impact and a more balanced distribution of the dynamic load in the median area.The oscillations, although with low amplitude, are well-defined and with constant periodicity, which denotes a robust elastic behavior and a good capacity of the structure to respond in a controlled manner. The positioning of sensor A2, less exposed to direct contact, explains both the reduced amplitudes and the stability of the response. This result emphasizes the importance of choosing the measurement points for the correct characterization of the dynamic response.

Accelerometer A1 response – 3 m run, subject 40 kg, position P2, test 3In the third test, accelerometer A1 recorded the largest displacements of all the tests performed: +25.9 mmnand −34.2 mm. These very high values indicate either a particularly violent impact or the occurrence of a local resonance phenomenon.

The shape of the graph suggests unstable initial oscillations, with large amplitudes and relatively slow attenuation, which confirms the intense stress on the frontal area. This behavior can be correlated with a particular positioning of the subject or with an uneven application of force.

The results could also indicate the beginning of a material fatigue process or a reduction in the elastic performance of the elements in the monitored area.

Comparative analysis between dynamic responses. Maximum displacement amplitude: In all cases, A1 recorded larger displacements than A2. For example, in Sample 1, A1 reached ±22.2– 23.4 mm, while A2 only ±6–7.5 mm.

This contrast highlights the fact that the frontal area takes the direct load, while the median area is less affected. Evolution of amplitudes on samples: In A1, a constant increase in maximum displacements between samples is noted (2.22 cm → 2.47 cm, 3.42 cm), which can be explained by a more energetic application of force or by the accumulation of structural fatigue effects. In A2, the values remain stable, with minor variations, confirming the stability of the median area.Influence of running distance:

For A2, the difference between the 3 m and 5 m runs was insignificant (7.50 mm vs. 7.81 mm), indicating that the additional energy is not efficiently transmitted to the edge of the structure.Symmetry of response: In Trial 2, A1 recorded asymmetric values (+18.5 mm vs. −24.7 mm), confirming the sensitivity of the frontal zone to lateral landings. In contrast, A2 maintained a more balanced response, indicating a reduced influence of the impact position.Oscillation damping: In A1, the damping became progressively slower between trials, suggesting a decrease in the damping efficiency in the frontal zone.

In A2, oscillations were consistently well controlled, confirming its stabilizing role *(Middelkoop, C. (2019)*. The results show that the elastic structure exhibits different behavior depending on the impact

position. The frontal zone (A1) is more sensitive, registers large amplitudes and is strongly influenced by the exact position of the contact. The middle zone (A2) exhibits a stable behavior, with low amplitudes and constant damping, demonstrating its role as a buffer and dissipative zone.These findings highlight the importance of a differentiated design of stiffness and damping, so that the structure can respond uniformly and safely to varying dynamic loads

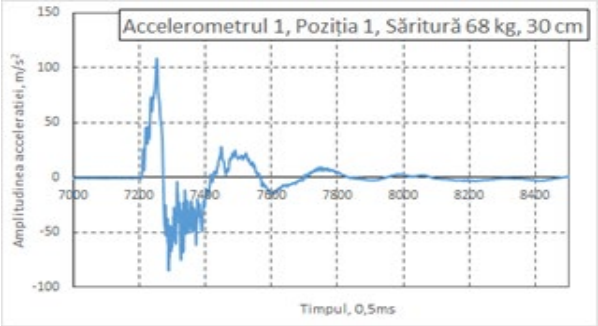

Fig. 9 - Accelerometer A1

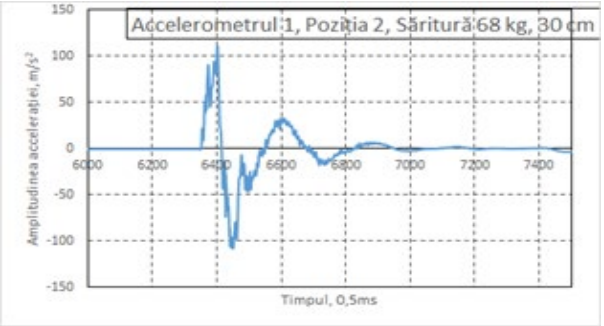

Fig. 10 - Accelerometer A1

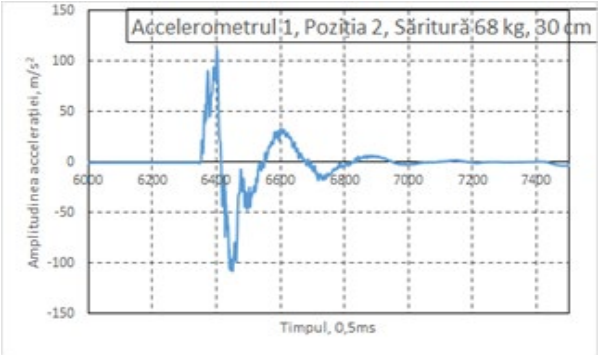

Fig. 11 - Accelerometer A1

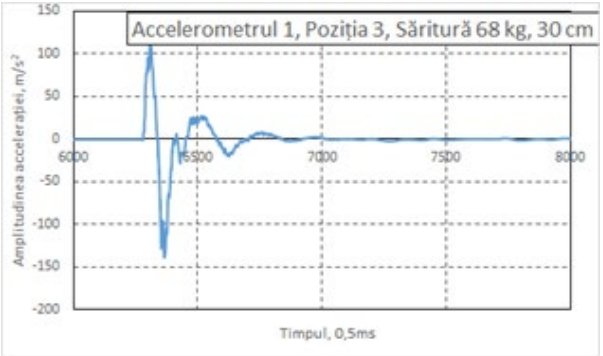

Fig. 12 - Accelerometer A1

Interpretation of experimental resultsAnalysis of the signals obtained for the subject with a mass of 68 kg, in the case of a controlled fall from 30 cm.From the evaluation of the signals recorded by the accelerometer A1, centrally located 70 mm from the front edge of the elastic structure, for a jump from a height of 30 cm (lateral position at 35 cm), it is found that acceleration values of over 100 m/s² are reached in all three positions investigated (140 mm, 330 mm and 530 mm from the front end).

However, the amplitudes and the vibration regime differ, indicating a progressive damping from position 1 to position 3.Position 1 (above accelerometer A1): the maximum acceleration reached values of +108.6 m/s² and −84.2 m/s².² *(Lehmann, T., Lorz, A., Schleichardt, A., Naundorf, F., Knoll, K., Eckardt, F., & Witte, K. (2020).*

The initial oscillation is pronounced, especially under the upper plate, and the duration of the damping was about 1200 ms.Position 2 (≈260 mm from A1): the amplitudes increase to +110.8 m/s² and −105.2 m/s², but the number of undulations is reduced, and the damping occurs more quickly, in about 1000 ms.Position 3 (≈460 mm from A1, close to the free end): the accelerometer recorded maximum values of +115.9 m/s² and −139.2 m/s².

However, the damping is accelerated (≈800 ms), and the positive/negative alternations are less, which suggests more efficient energy dissipation in the free area of the structure. In conclusion, the amplitudes increase from position 1 to position 3, but the damping duration decreases significantly, confirming the existence of zonal differences in stiffness and energy dissipation.

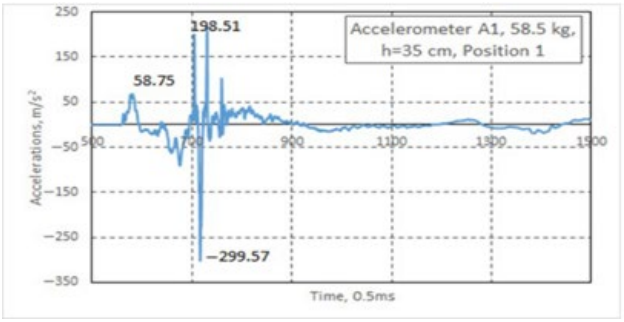

Fig. 13 - Accelerometer A1

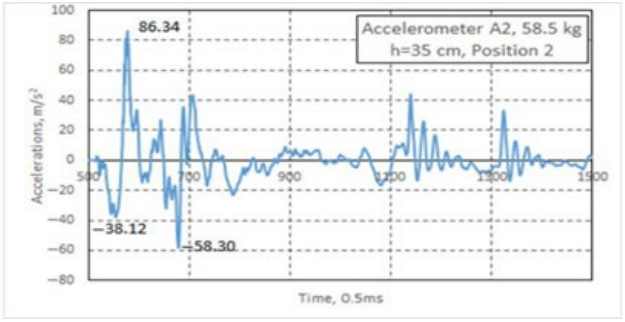

Fig. 14 - Accelerometer A2

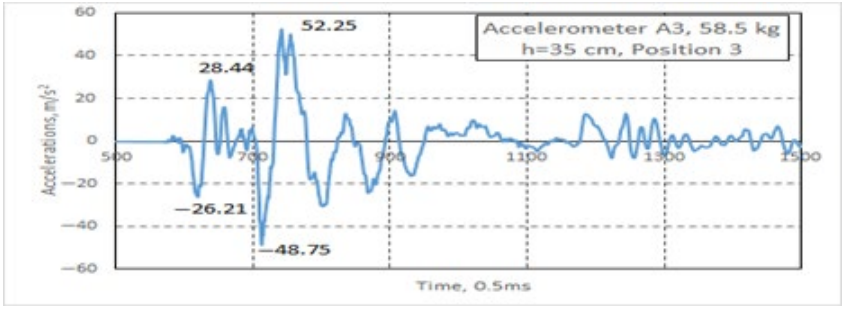

Fig. 15 - Accelerometer A2

Experimental resultsFor Position 1 (A1, frontal area) maximum amplitudes of +198.51 m/s² and −299.57 m/s² were recorded, preceded by an initial oscillation of +58.75 m/s². The signal shows sudden variations immediately after impact, followed by a progressive damping, which confirms the intense stress on the conical springs responsible for absorbing the shock.In Position 2 (A2, medial area) the maximum values were +86.34 m/s², −38.12 m/s² and −58.30 m/s².

The oscillations had a lower amplitude than in A1, but with a more complex structure, marked by multiple alternations. This behavior reflects the role of the medial area as a transitional element, where the conical and cylindrical springs interact.For Position 3 (A3, posterior area) the amplitudes reached +52.25 m/s² and −48.75 m/s², with moderate initial values (+28.44 m/s² and −26.21 m/s²).The signal attenuated more quickly, presenting low intensity and relatively regular oscillations, characteristic of energy dissipation through the cylindrical springs.

Comparative analysisThe results show a progressive decrease in amplitudes from the front to the rear of the structure. Position A1 highlights the maximum amplitudes, corresponding to direct shock absorption; A2 reflects the transfer and redistribution of energy; and A3 confirms the dissipation and subsequent stabilization. This distribution demonstrates the existence of distinct local stiffnesses and the differentiated role of conical and cylindrical springs in the dynamic behavior of the assembly.

CONCLUSIONS

1. The 3SLP elastic structure exhibits its dynamic behavior through the balance between the stiffness of the plates, the characteristics of the conical and cylindrical springs and the assembly method, elements that determine the overall performance.
2. The athlete's mass directly influences the amplitude and duration of the oscillations; the values increase proportionally with the weight, which confirms the sensitivity of the assembly to variable dynamic loads.
3. The fall height has a major effect on the maximum amplitudes: the tests at 60 cm produced larger and more difficult to dampen oscillations compared to those at 30 cm.
4. The frontal zone (A1) absorbs the initial shock and presents the largest displacements, confirming the dominant role of the conical springs in absorbing the impact energy.
5. The median zone (A2) reflects a stable elastic transition, with moderate amplitudes and constant damping, due to the interaction between the conical and cylindrical springs.
6. The posterior area (A3) has a predominantly dissipative role, the amplitudes being reduced and the oscillations quickly die out, which contributes to the stabilization of the entire assembly.
7. The experimental results provide a basis for optimizing the design and standardizing gymnastics equipment, ensuring both increased performance and increased user safety.

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KINEMATIC ANALYSIS OF A DISINFECTION SPIDER ROBOT
/
ANALIZA CINEMATICĂ A UNUI ROBOT PĂIANJEN DE DEZINFECȚIE

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Keywords: *arachnids, structure, kinematics, rotation angle.*

ABSTRACT
In the medical domain, surface disinfection has been a critical factor in the performance of all procedures. In this regard, it has been found that the use of robots specifically designed for this purpose is the best option. This paper examines the kinematics of a spider robot used in the disinfection process of a room. It has a robotic arm attached, which could be used to disinfect surfaces less accessible to conventional robots. The kinematic analysis was performed both on the body of the robot and on the robotic arm, at the end of which an ultraviolet light lamp was attached.

REZUMAT
În domeniul medical, dezinfectarea suprafețelor a reprezentat un factor foarte important în desfășurarea tuturor procedurilor. În acest sens, s-a constatat că utilizarea roboților special proiectați pentru acest scop este cea mai bună opțiune. În cadrul acestui articol, s-a studiat cinematica unui robot păianjen, utilizat în procesul de dezinfecție a unei camere. Acesta are atașat un braț robotic, cu care poate dezinfecta suprafețe mai puțin accesibile roboților convenționali. Analiza cinematică a fost realizată atât asupra corpului robotului, cât și asupra brațului ce are atașat la capăt o lampă cu lumină ultravioletă.

INTRODUCTION

A robot is a system capable of performing autonomous tasks, which can be operated by an operator or by a computer program *(Karakurt et al., 2015; Kyrarini and Lygerakis, 2021)*. Disinfection robots have been an essential aid for medical staff, both during and after the COVID-19 pandemic, as sanitization of medical wards is necessary for proper patient care.

One effective method is the use of robots which utilize ultraviolet (UV) light for disinfection *(Gasparetto and Vidoni, 2008).* The most widely used type of robot on the market is the wheeled robot model, as shown in *(Gasparetto and Vidoni, 2008).* However, it has been found that for some more difficult to reach places, it would be ideal to use another type of robot, as shown in various articles.

The spider robot, an alternative to the conventional type of robots with wheels, comes with a number of additional advantages over other models on the market.

The spider robot can replicate the motion of the arachnids *(Ikhar and Lanjewar, 2023),* having better flexibility and a wide variety of movements. Over the years, many such robotic systems have been created and studied.

In *(Karakurt et al., 2015),* a simplified mechanical model was developed for a spider robot with a specific structure: six limbs and three segments. This model was created since it is very difficult to synthesize an exact model for a robot which has limbs based on a multi-link structure, such as one with a total of twenty-four mobilities *(Karakurt et al., 2015; Craifaleanu and Negroiu, 2024).*

In *(Chen et al., 2023; Craifaleanu and Negroiu, 2024; Karakurt et al., 2015; Kravchenko, 2023; Manikandan and Sandeep, 2023),* more models of quadrupedal spider robots have been designed, in order to mimick the spider walk. These models have similar mechanical structures, but different electronic control systems *(Craifaleanu and Negroiu, 2024).*

MATERIALS AND METHODS

The paper presents a spider robot, which uses UV light devices to disinfect various surfaces. The spider robot kit BITMI 10158 (Fig. 1) was used as a model, to which a stand with four UV lamps and a robotic arm were attached (Fig. 2, 3).

The improvement is represented by the addition of the robotic arm, which has a lamp and a sensor attached at the end. This device is more convenient for disinfection in places that are difficult to reach for other types of robots, such as the underside of a chair or a toilet seat.

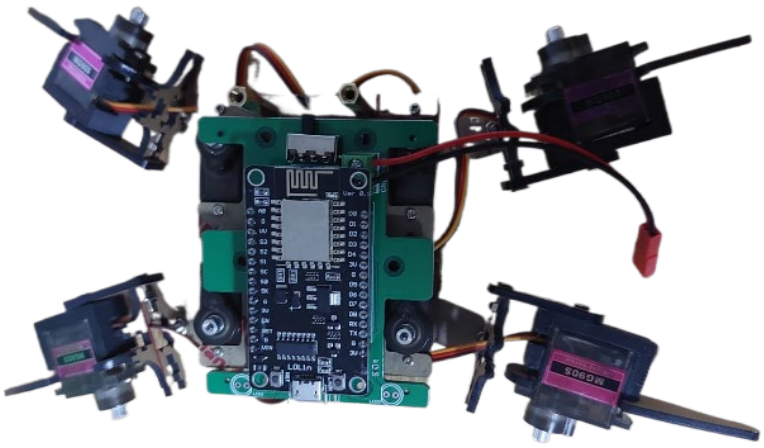

Fig. 1 - BITMI 10158 robot kit

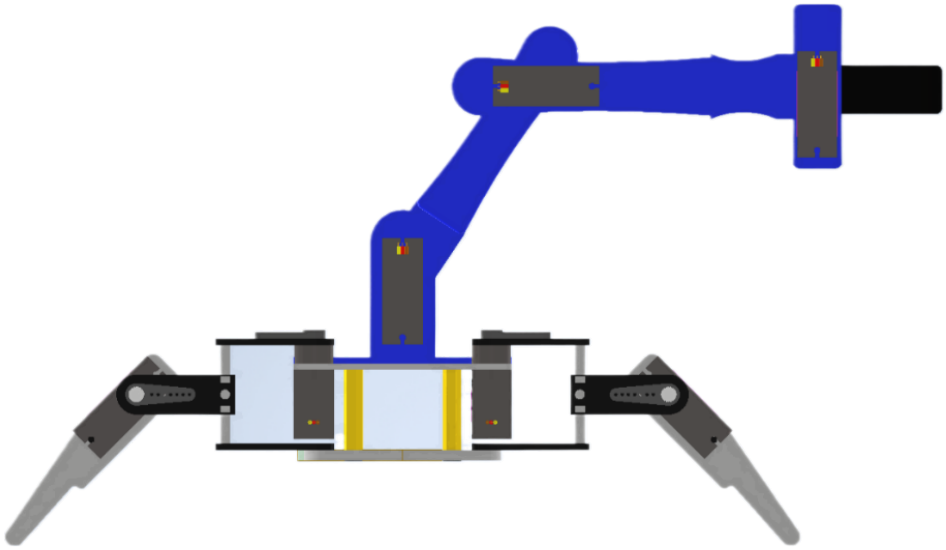

Fig. 2 - 3D model of presented robot

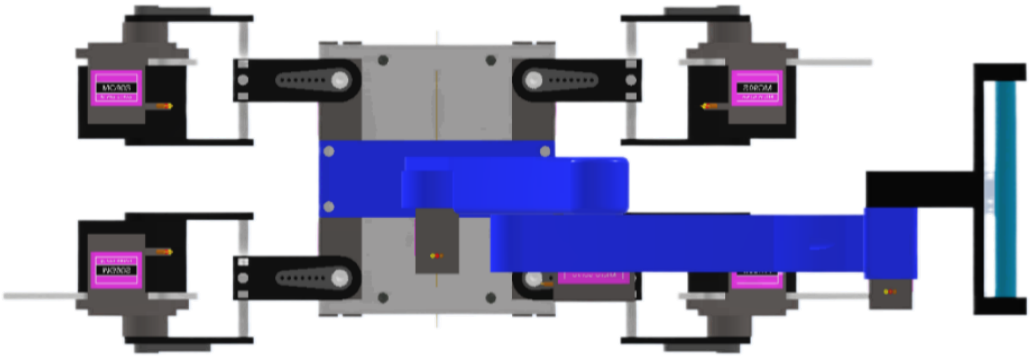

Fig. 3 - A top view of the 3D model of the robot

A kinematic analysis for the entire system is presented, in which the velocities and accelerations of the robot legs and the arm attached to the robot are determined.

In the following pages, some of the study methods used for kinematic calculations were presented *(Radoi and Deciu).*

The first method involves the kinematics of the relative motion of a rigid body. For this method, three coordinate systems were defined: T_0, fixed, T_1, in motion with respect to T_0 and T_2, which is connected to the rigid body. System T_2 is in motion with respect to both T_0 and T_1. A point M of the rigid body is considered (Fig. 4).

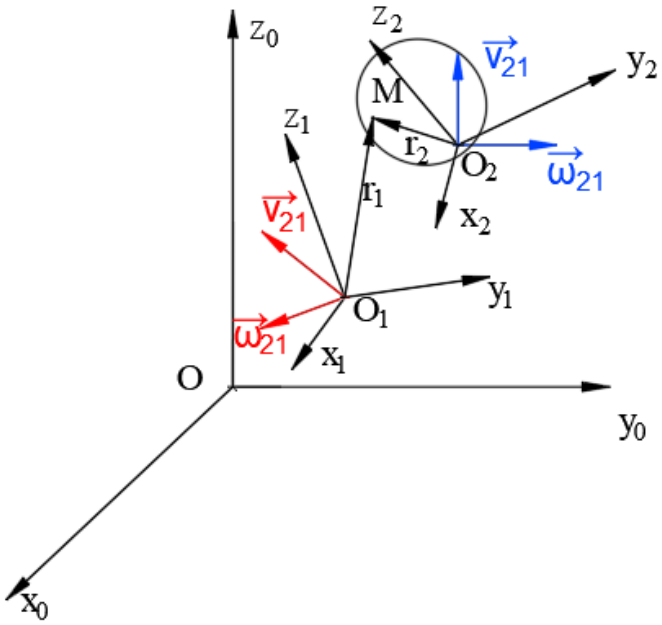

Fig. 4 - The three systems and their respective elements *(Radoi and Deciu)*

The motion of an arbitrary system T_j with respect to another system, T_i is defined by the velocity $\vec{v}_{ji}$ and by the acceleration $\vec{a}_{ji}$ of the origin O_j with respect to T_i, as well as by the angular velocity vector $\vec{\omega}_{ji}$ and by the angular acceleration vector $\vec{\varepsilon}_{ji}$ [9, p.274-275].

The composition formula of the velocities in the relative motion of a material point *(Radoi and Deciu)*,

$$\vec{v}_a = \vec{v}_r + \vec{v}_t, \tag{1}$$

Leads to the following relation:

$$\vec{v}_{20}^{M} = \vec{v}_{10} + \vec{v}_{21} + \vec{\omega}_{10} \times \vec{r}_1 + \vec{\omega}_{21} \times \vec{r}_2. \tag{2}$$

In this relation, $\vec{r}_i$ represents the position vector of point *M*, with respect to origin O_i.

For an arbitrary number *n* of reference systems, formula (2) can be generalized as

$$\vec{v}_{n0}^{M} = \sum_{i=1}^{n} \vec{v}_{i,i-1} + \sum_{i=1}^{n} \vec{\omega}_{i,i-1} \times \vec{r}_i. \tag{3}$$

Similarly, the absolute acceleration of point *M* is

$$\vec{a}_a = \vec{a}_r + \vec{a}_t + \vec{a}_c, \tag{4}$$

which leads to

$$\begin{aligned} \vec{a}_{20}^{M} = {} & \vec{a}_{10} + \vec{a}_{21} + \vec{\varepsilon}_{10} \times \vec{r}_1 + \vec{\varepsilon}_{21} \times \vec{r}_2 + \\ & + \vec{\omega}_{10} \times (\vec{\omega}_{10} \times \vec{r}_1) + \vec{\omega}_{21} \times (\vec{\omega}_{21} \times \vec{r}_2) + 2\vec{\omega}_{10} \times (\vec{v}_{21} + \vec{\omega}_{21} \times \vec{r}_2). \end{aligned} \tag{5}$$

Similarly to formula (2), formula (5) can be generalized for an arbitrary number *n* of reference systems *(Radoi and Deciu)*:

$$\vec{a}_{n0}^{M} = \sum_{i=1}^{n} \vec{a}_{i,i-1} + \sum_{i=1}^{n} \vec{\varepsilon}_{i,i-1} \times \vec{r}_i + \sum_{i=1}^{n} \vec{\omega}_{i,i-1} \times \left(\vec{\omega}_{i,i-1} \times \vec{r}_i\right) + \\ + 2\sum_{i=1}^{n}\sum_{j=1}^{i-1} \vec{\omega}_{j,j-1} \times \left(\vec{v}_{i,i-1} + \vec{\omega}_{i,i-1} \times \vec{r}_i\right). \quad (6)$$

The second method involves numerical derivation. The relationships for *x* components of velocity and acceleration of a point are *(Radoi and Deciu)*:

$$v_{x_i} \cong \frac{x_{i+1} - x_{i-1}}{t_{i+1} - t_{i-1}} \quad (i = 1,...,n), \quad (7)$$

$$a_{x_i} \cong \frac{x_{i+1} - 2x_i + x_{i-1}}{(t_{i+1} - t_i)^2} \quad (i = 1,...,n). \quad (8)$$

For *y* and *z* components, similar relations are valid:

$$v_{y_i} \cong \frac{y_{i+1} - y_{i-1}}{t_{i+1} - t_{i-1}} \quad (i = 1,...,n), \quad (9)$$

$$a_{y_i} \cong \frac{y_{i+1} - 2y_i + y_{i-1}}{(t_{i+1} - t_i)^2} \quad (i = 1,...,n), \quad (10)$$

$$v_{z_i} \cong \frac{z_{i+1} - z_{i-1}}{t_{i+1} - t_{i-1}} \quad (i = 1,...,n), \quad (11)$$

$$a_{z_i} \cong \frac{z_{i+1} - 2z_i + z_{i-1}}{(t_{i+1} - t_i)^2} \quad (i = 1,...,n). \quad (12)$$

The kinematic analysis is performed for the robotic arm and for one leg of the spider robot. First, the motions of the servomotors that drive the robot will be defined.

The robot (Fig. 5) has eleven servomotors built into its structure. The servomotors in points O_2, O_3, O_4, O_5, are designed to drive the legs of the robot (as shown in Fig. 6). Those in O_2 and O_4 rotate about O_iZ_i axis with angles ψ_i (*i* = 2, 4), respectively, while servomotors in O_3 and O_5 rotate about the O_iY_i axis, with angles θ_i (*i* = 3, 5), respectively (Fig. 7).

The servomotors in points O_6, O_7, O_8 are used to operate the robot arm. These servomotors rotate about O_iY_i axis with angles θ_i (*i* = 6, 7, 8).

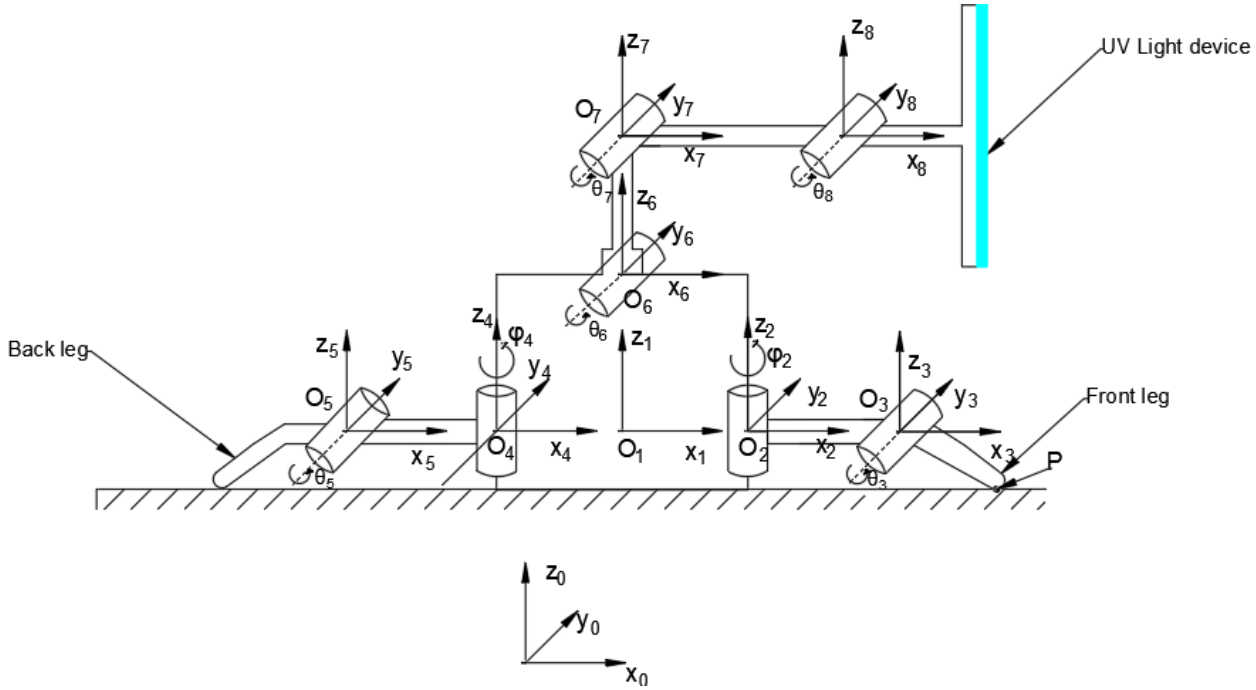

Fig. 5 - Kinematic structure of the robot

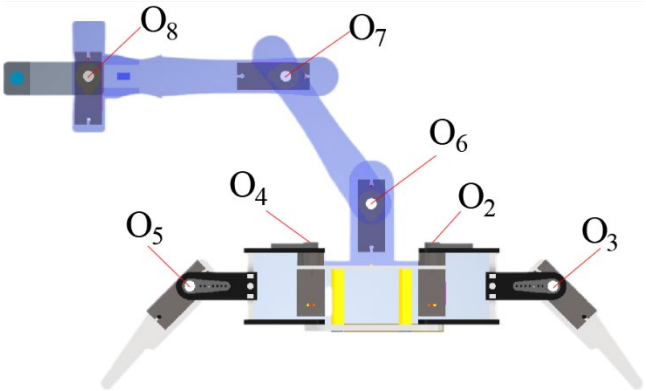

Fig. 6 - The location of the servomotors

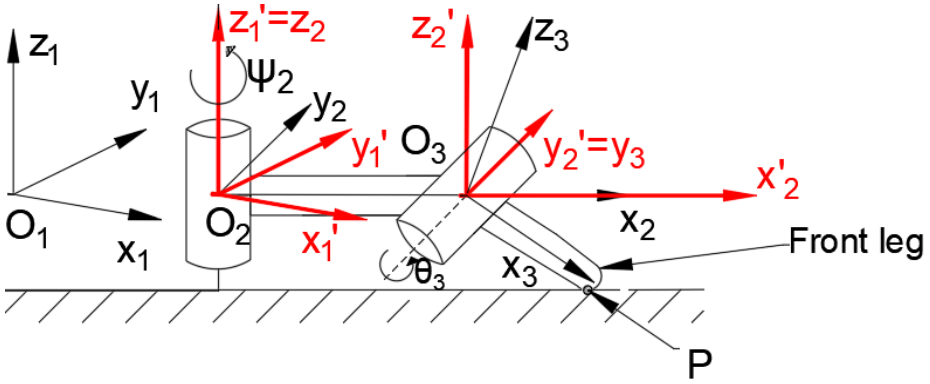

Fig. 7 - Kinematic model of the robot leg

The velocity of point P (Fig. 7) (which is the tip of the foot, i.e. the point of the robot leg which touches the fixed surface), with respect to reference system $O_1x_1y_1z_1$ (connected to the chassis) is:

$$\vec{v}_{31}^{P} = \sum_{i=2}^{3} \vec{v}_{i,i-1} + \sum_{i=2}^{3} \vec{\omega}_{i,i-1} \times \vec{r}_i \qquad (13)$$

The acceleration of point *P* is

$$\vec{a}_{31}^{P}=\sum_{i=2}^{3}\vec{a}_{i,i-1}+\sum_{i=2}^{3}\vec{\varepsilon}_{i,i-1}\times\vec{r}_i+\sum_{i=2}^{3}\vec{\omega}_{i,i-1}\times\left(\vec{\omega}_{i,i-1}\times\vec{r}_i\right)+$$
$$+2\sum_{i=1}^{3}\sum_{j=1}^{i-1}\vec{\omega}_{j,j-1}\times\left(\vec{v}_{i,i-1}+\vec{\omega}_{i,i-1}\times\vec{r}_i\right), \quad (14)$$

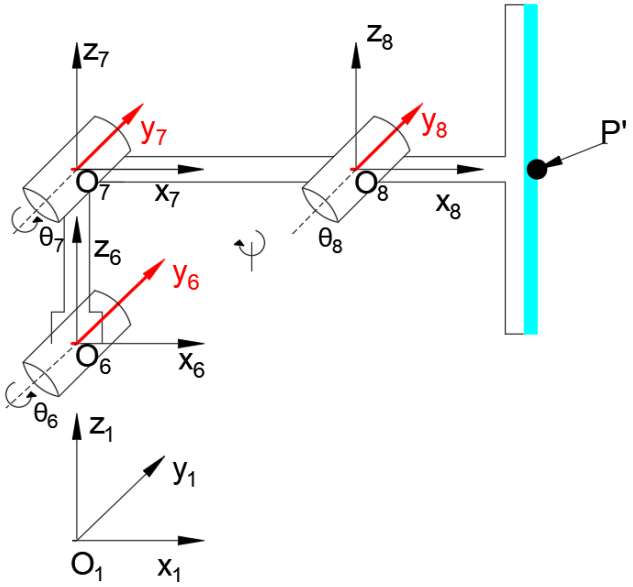

Fig. 8 - Kinematic schematics for the robot arm

The velocity and acceleration of point P' (Fig. 8) (which is the tip of the end effector), with respect to reference system $O_1x_1y_1z_1$ are, according to formulae (3) and (6), respectively:

$$\vec{v}_{81}^{P'}=\vec{v}_{61}+\sum_{i=7}^{8}\vec{v}_{i,i-1}+\vec{\omega}_{61}\times\vec{r}_1+\sum_{i=7}^{8}\vec{\omega}_{i,i-1}\times\vec{r}_i \quad (15)$$

$$\vec{a}_{81}^{P'}=\vec{a}_{61}+\vec{\varepsilon}_{61}\times\vec{r}_6+\vec{\omega}_{61}\times\left(\vec{\omega}_{61}\times\vec{r}_6\right)+2\sum_{i=7}^{8}\vec{\omega}_{61}\times\left(\vec{v}_{i,i-1}+\vec{\omega}_{i,i-1}\times\vec{r}_i\right)+$$
$$+\sum_{i=7}^{8}\vec{a}_{i,i-1}+\sum_{i=7}^{8}\vec{\varepsilon}_{i,i-1}\times\vec{r}_i+\sum_{i=7}^{8}\vec{\omega}_{i,i-1}\times\left(\vec{\omega}_{i,i-1}\times\vec{r}_i\right)+ \quad (16)$$
$$+2\sum_{i=7}^{8}\sum_{j=7}^{i-1}\vec{\omega}_{j,j-1}\times\left(\vec{v}_{i,i-1}+\vec{\omega}_{i,i-1}\times\vec{r}_i\right).$$

Table 1

Rotation angles for the active joints of the robot leg

Rotation angles	ψ_2	θ_3
Values	$0.....\frac{\pi}{2}$	$0.....\frac{\pi}{2}$

Table 2

Rotation angles for the active joints of the robot arm

Rotation angles	θ_6	θ_7	θ_8
Values	$0.....\frac{\pi}{4}$	$0.....\frac{\pi}{4}$	$0.....\frac{\pi}{2}$

Each angle varies in the time interval t_1=0.... t_n=10s, according to a special law of motion. For example, the law of motion for angle θ_3 is:

$$\theta_3 = a_3 + 0.5 \cdot (b_3 - a_3) \cdot [1 - \cos(\omega_3 t)], a_3 = 0; b_3 = \frac{\pi}{2} \quad (17)$$

In the following paragraphs, the results of the kinematic analysis for the front leg of the robot are shown. Figure 9 displays the variations of the rotation angles of joints O_2 and O_3 of the leg, with respect to time.

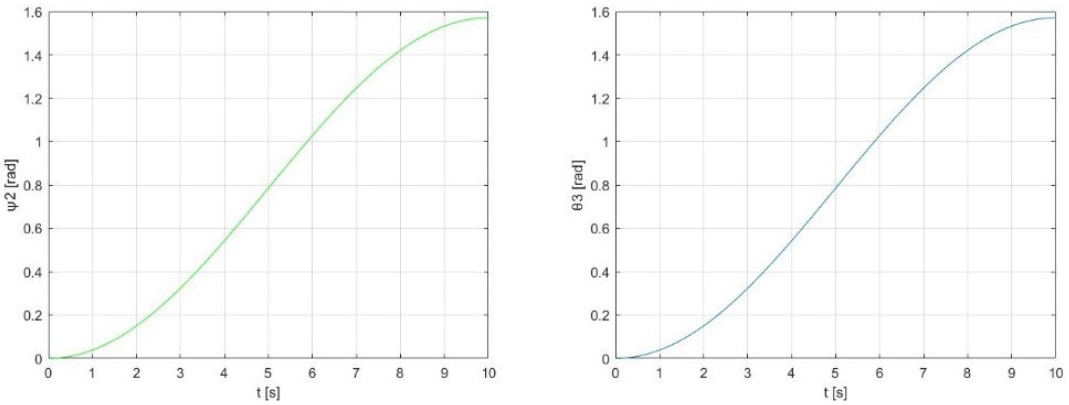

Fig. 9 - Time variations of rotation angles for O_2 and O_3, respectively

The variations of the angular velocities and accelerations of joints O_2 and O_3 of the leg can be displayed in a similar manner.

Next, the variations of the coordinates of point P, with respect to time are displayed in Figure 10. Also, the variations of the velocity and acceleration components of the same point are displayed in Figure 11 and 12, respectively.

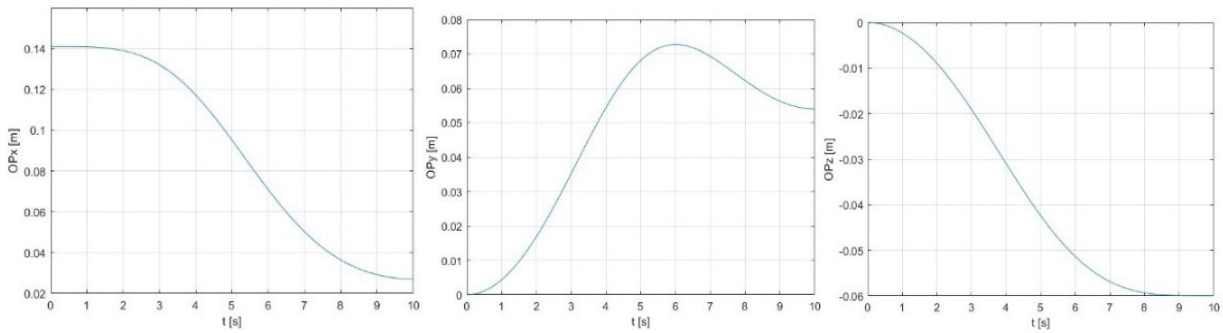

Fig. 10 - Time variations of coordinates of point *P*

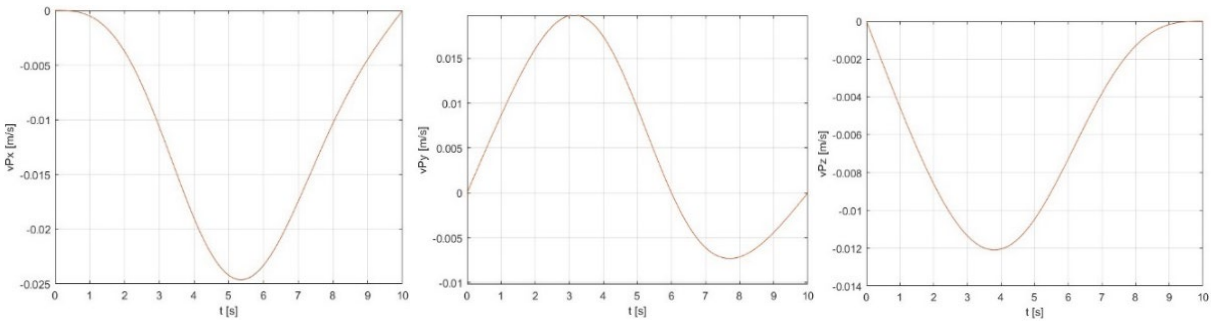

Fig. 11 - Time variations of velocity components of point *P*

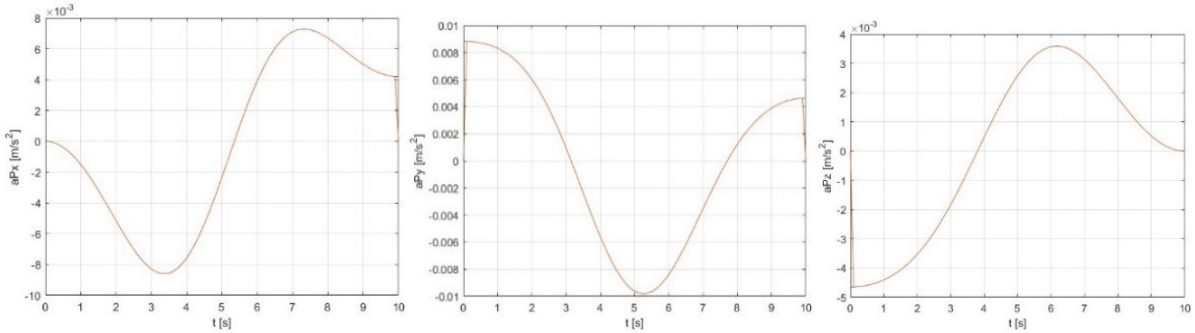

Fig. 12 - Time variations of acceleration components of point *P*

For the arm attached to the robot, Figure 13 displays the variations of the rotation angles of the joints. The velocity and acceleration components of joints O_6, O_7 and O_8 can be displayed in a similar manner.

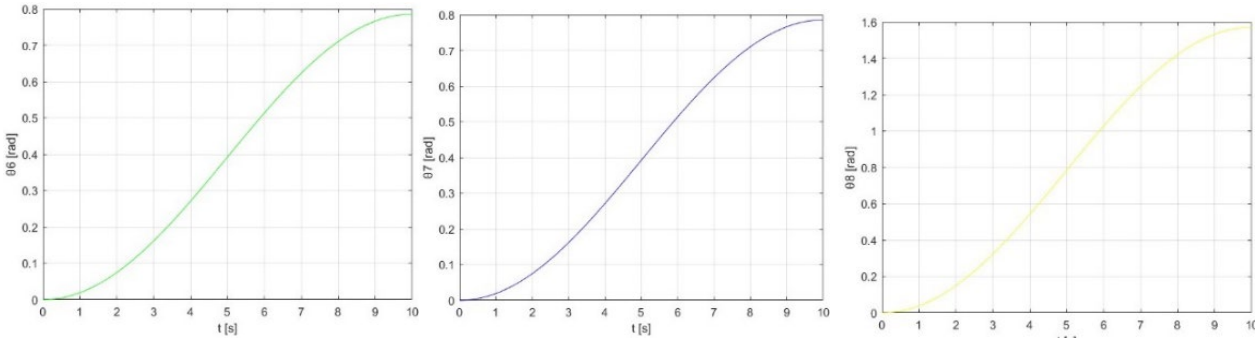

Fig. 13 - Time variations of rotation angles for O_6, O_7 and O_8, respectively

Figure 14 displays the variation of the coordinates of point P', with respect to time. The variations the of velocity and acceleration components of the same point are displayed in Figures 15 and 16.

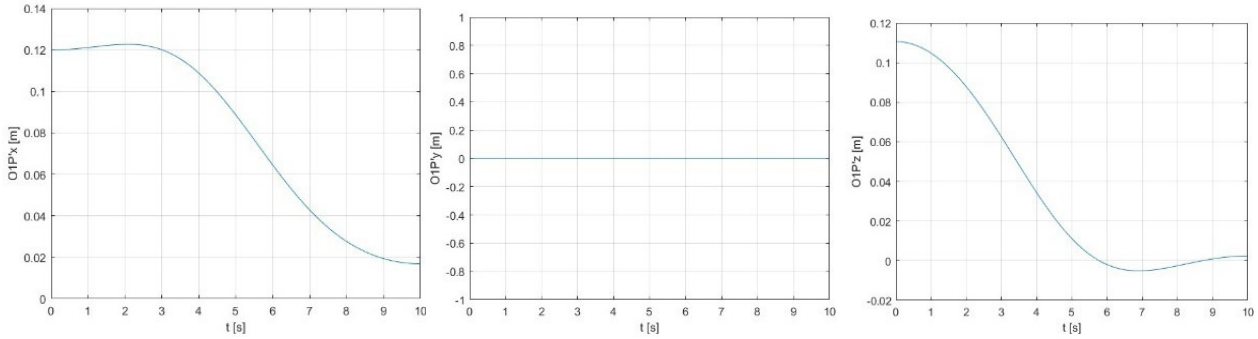

Fig. 14 - Time variations of coordinates of point *P'*

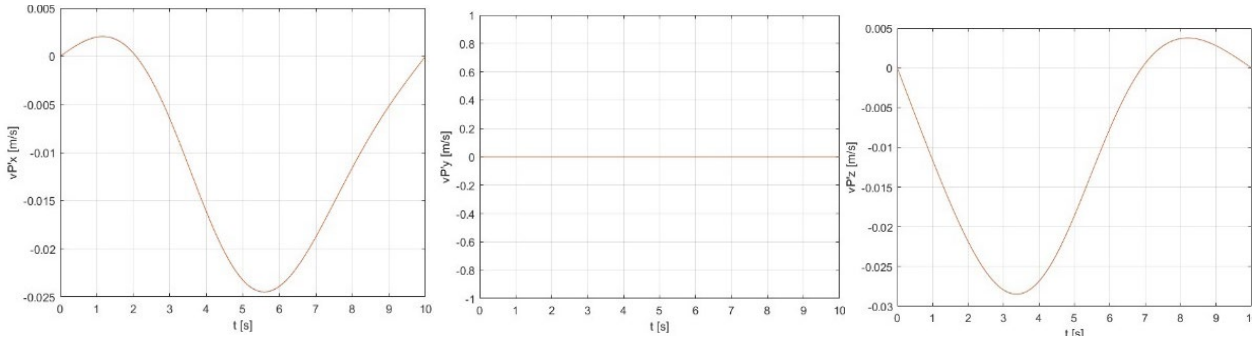

Fig. 15 - Time variations of velocity components of point *P'*

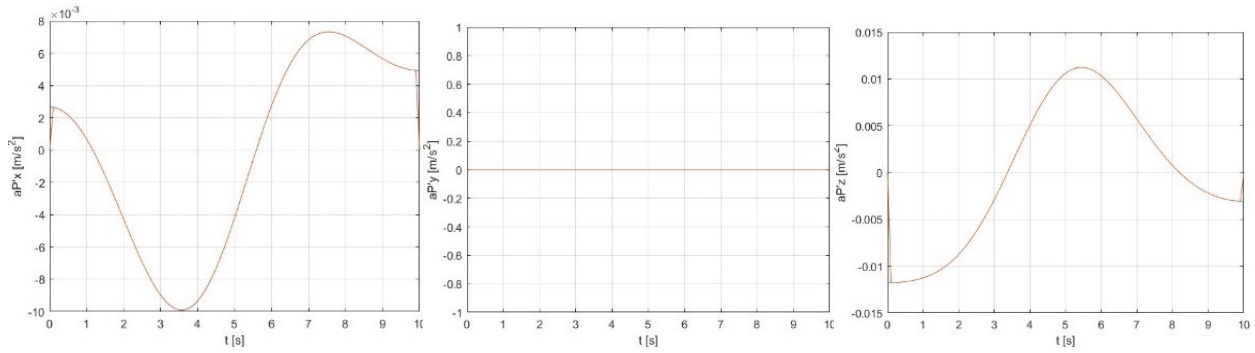

Fig. 16 - Time variations of acceleration components of point *P'*

The variations of the velocity and acceleration components with respect to time have been calculated using two derivation methods: analytical (with blue) and numerical (with orange). It can be seen in each figure, that, at the chosen representation scales, the two variation curves are superimposed, which verifies the accuracy of the calculations. Figure 17 shows a zoomed view of the curves in the first part of Figure 16.

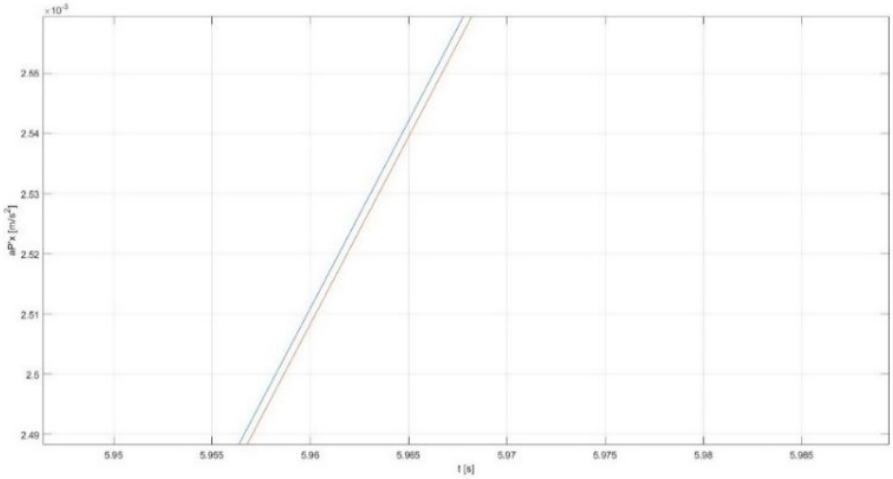

Fig. 17 - A close-up view of the first graph

CONCLUSIONS

The presented robot is designed for disinfection of hard-to-reach areas.

This disinfection process can be performed using the RRR robotic arm attached to a four-legged spider robot, which represents the improved version of a commercial model.

The chassis has been designed to be simple to assemble and repair, and the robot arm attached to it is made of 3D printed parts. In terms of construction and maintenance, the robot is affordable and can be easily upgraded.

A kinematic analysis of a leg and of the robotic arm has been performed and the results obtained by two different methods are in very good agreement.

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DEEP LEARNING - POWERED APP FOR EARLY DETECTION OF TOMATO AND PEPPER LEAF DISEASES

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APLICAȚIE BAZATĂ PE DEEP LEARNING PENTRU DETECTAREA TIMPURIE A BOLILOR FRUNZELOR DE ROȘII ȘI ARDEI

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Keywords: *image analysis, plant* phenotyping*, computer vision, leaf classification*

ABSTRACT

This paper presents the development of an innovative deep learning-based application for automatic and real-time detection of tomato and pepper leaf diseases in protected environments. The application uses the YOLO9 (You Only Look Once version 9) algorithm trained on diversified datasets from Roboflow and Kaggle platforms, totaling over 10,000 labeled images. The integrated system includes an HD webcam for image capture, preprocessing modules for visual data optimization, and an alert system for user notifications. The application performs real-time detection with optimized processing rates, implementing advanced functions for automatic incident recording in CSV format for subsequent analysis. Results demonstrate system efficiency in early identification of diseases such as Early Blight, Late Blight, Septoria Leaf Spot, and Leaf Miner, contributing to improved disease management in protected crops.

REZUMAT

Această lucrare prezintă dezvoltarea unei aplicații inovatoare bazate pe deep learning pentru detectarea automată și în timp real a bolilor frunzelor de tomate și ardei în spații protejate. Aplicația utilizează algoritmul YOLO9 (You Only Look Once versiunea 9) antrenat pe seturi de date diversificate provenite din platformele Roboflow și Kaggle, totalizând peste 10.000 de imagini etichetate. Sistemul integrat include o cameră web HD pentru capturarea imaginilor, module de preprocesare pentru optimizarea datelor vizuale, și un sistem de alertă pentru notificarea utilizatorilor. Aplicația realizează detectarea în timp real cu o rată de procesare optimizată, implementând funcții avansate de salvare automată a incidentelor într-un format CSV pentru analiză ulterioară. Rezultatele demonstrează eficiența sistemului în identificarea precoce a bolilor precum Early Blight, Late Blight, Septoria Leaf Spot și Leaf Miner, contribuind la îmbunătățirea managementului bolilor în culturile protejate.

INTRODUCTION

Leaf diseases are one of the main threats to the productivity of tomato and pepper crops, causing significant yield losses globally (*Jelali, 2024*). Early and accurate detection of these diseases is essential to implement appropriate control measures and minimize the economic impact on agricultural producers (*Jafar et al., 2024*). Traditional methods of disease identification, based on visual observation and the experience of specialists, are often limited by subjective factors, high costs, and time required for diagnosis (*Wang & Liu, 2024*).

Recent advances in artificial intelligence, especially in deep learning and computer vision technologies, offer promising solutions for automating the process of plant disease detection (*Pacal et al., 2024; Abdullah et al., 2024*).

Algorithms based on convolutional neural networks (CNNs) have demonstrated remarkable capabilities in recognizing and classifying medical and agricultural images, achieving comparable or superior human performance in many specific cases. Due to limited dataset availability in machine learning-based research, studies on plant recognition and disease detection are significantly affected, however, recent efforts have made notable progress in bridging this gap (*Jelali, 2024*).

The YOLO (You Only Look Once) algorithm, in its evolutionary versions, has revolutionized the field of real-time object detection, offering an optimal balance between accuracy and processing speed (*Guo,*

2024; Zayani et al., 2024). Unlike traditional detection methods that process the image in multiple stages, YOLO analyzes the entire image in a single pass, making simultaneous predictions for the location and classification of detected objects. This approach makes it ideal for applications that require real-time response, such as continuous monitoring of plant health in protected spaces.

Tomato and pepper crops are vulnerable to a wide range of fungal, bacterial and viral pathogens that primarily affect the leaves (*Mathew & Mahesh, 2022; Suryaprabha, 2024*). Common diseases include Early Blight, Late Blight, Septoria Leaf Spot and Leaf Miner, each with distinctive visual characteristics that can be exploited by computer vision algorithms for automatic identification.

Implementing automated detection systems in protected spaces offers significant advantages over conventional methods. Continuous 24/7 monitoring, reduced need for frequent manual inspections, early detection before significant visible symptoms appear, and automated incident documentation for epidemiological analysis are just some of the benefits of this advanced technological approach (*Sun et al., 2025*).

This paper describes the development and implementation of an innovative application based on the YOLO9 algorithm for the automatic detection of tomato and pepper leaf diseases in greenhouse conditions.

The integrated system combines high-resolution video capture technologies with advanced image preprocessing and real-time detection algorithms, providing a complete solution for plant health monitoring in precision agriculture.

MATERIALS AND METHODS

System configuration and application architecture

The application developed for the detection of tomato and pepper leaf diseases is based on a modular architecture that integrates several advanced technological components. The system operates on a laptop platform equipped with an Intel Core i5-13600h processor, 16 GB RAM, and a dedicated Nvidia RTX 4060 graphics card for accelerating deep learning calculations.

The image acquisition component consists of an HD webcam with a minimum resolution of 1920x1080 pixels, capable of video capture at 30 fps. The camera is strategically positioned within the protected space to ensure optimal coverage of the monitoring areas, with automatic adjustments for the variable lighting conditions specific to greenhouses.

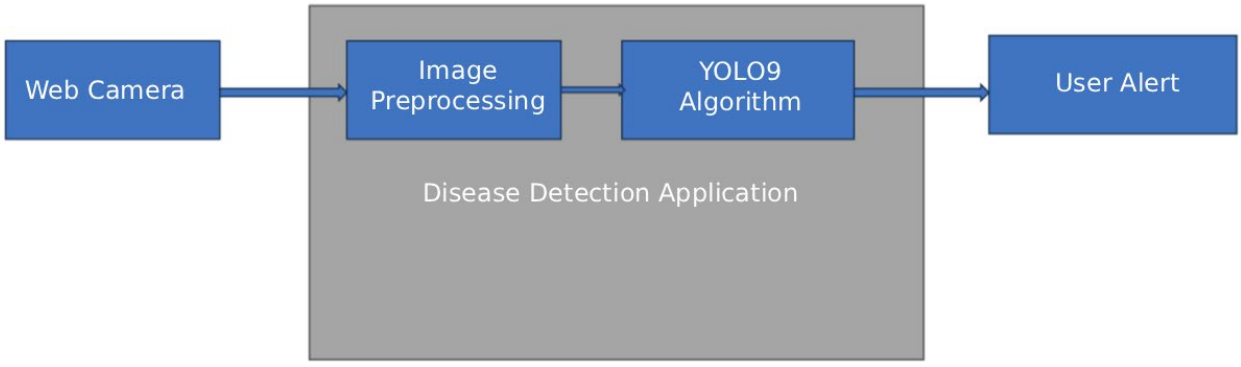

Fig. 1 - Block diagram of the application for detecting leaf diseases

Dataset preparation and processing

Two main datasets, specifically optimized for leaf disease detection, were used to train the YOLO9 model. For tomato crops, the "Tomato Leaf Disease" dataset available on the Roboflow platform was used, which contains 10,269 images distributed as follows: 9,236 images for training (90%), 867 images for validation (8%), and 166 images for testing (2%).

For pepper disease detection, a "superset" was created by concatenating multiple data sources from the Roboflow and Kaggle platforms. The resulting set contains 1,256 images, divided into: 1,130 images for training (90%), 100 images for validation (8%), and 26 images for testing (2%). This approach ensured the diversity necessary for robust training of the algorithm under varied conditions of capture and symptom manifestation.

Fig. 2 - Examples of images of tomato leaves affected by various diseases

All images were subjected to a standardized preprocessing process that includes auto-orientation to automatically correct image position, resizing to the standard 640x640 pixel size compatible with the YOLO9 architecture, and applying augmentations to improve the generalization ability of the model. The augmentations applied include 90° rotations in both directions and exposure adjustments within the range of ±8% to simulate the variable lighting conditions in the greenhouse.

Fig. 3 - Example image of an affected pepper leaf

Implementing and configuring the YOLO9 algorithm

The YOLO9 algorithm used represents the latest evolution of the YOLO family, optimized for real-time object detection with superior performance in terms of accuracy and speed *(Dai et al., 2024)*. The neural network architecture is based on an advanced convolutional backbone that extracts hierarchical features from images, followed by a feature aggregation neck and a detection head that generates final predictions.

The hyperparameter configuration for training included: batch size of 16 images to optimize GPU memory, initial learning rate of 0.001 with adaptive programming, 300 epochs for full training with early

stopping in case of overfitting, and loss functions optimized for multi-class detection. Training was performed on an NVIDIA RTX 4090 GPU configuration, with a total time of approximately 15 hours for each model (tomatoes and peppers).

Image preprocessing and optimization system

The preprocessing module implements several techniques to optimize image quality before analysis by YOLO9. Auto-orientation uses edge detection algorithms to identify the correct leaf orientation and automatically correct unwanted rotations. Resizing is performed using bicubic interpolation to maintain the quality of fine details, essential for identifying early symptoms.

The system also includes advanced brightness and contrast normalization functions to compensate for variable lighting conditions in the greenhouse, which are often encountered due to changes in time or day *(Kaur et al., 2024).* Noise filtering and sharpness enhancement are achieved by applying adaptive filters that preserve information relevant for disease detection.

Alert system architecture and data storage

The notification system implements a multi-level strategy to inform users about disease detection. Visual alerts appear as pop-ups on the graphical interface, containing information about the type of disease detected, the time of detection, and the coordinates of the affected area on the image. Optional sound alerts can be activated for situations that require immediate attention.

An innovative aspect of the application is the automatic incident recording system. Each confirmed detection is saved in a local CSV file, recording the following information: the exact timestamp of the detection, the type of disease identified, and the configuration parameters active at the time of detection. This data allows for subsequent statistical analysis to identify trends and optimize disease management strategies.

User interface and interactive features

The application's graphical interface is developed in an intuitive design that allows easy access to all system functionalities. Users can select their preferred capture device from the list of available cameras and configure the interface language (Romanian or English).

A key functionality consists of selecting the type of plant being monitored (tomatoes or peppers), which activates the corresponding YOLO model.

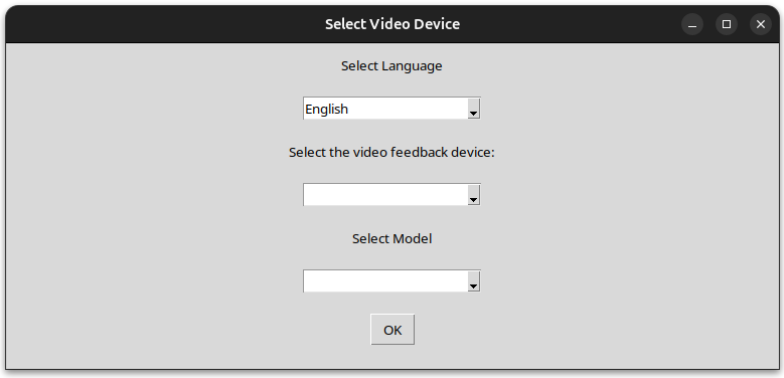

Fig. 4 - The initial application configuration interface

The control panel offers real-time adjustments for the detection confidence threshold (sensitivity), frame rate (FPS), and the threshold time for confirming persistent detections. Users can enable or disable audible alerts and configure pop-up notification suppression based on their work preferences and specific monitoring environment requirements.

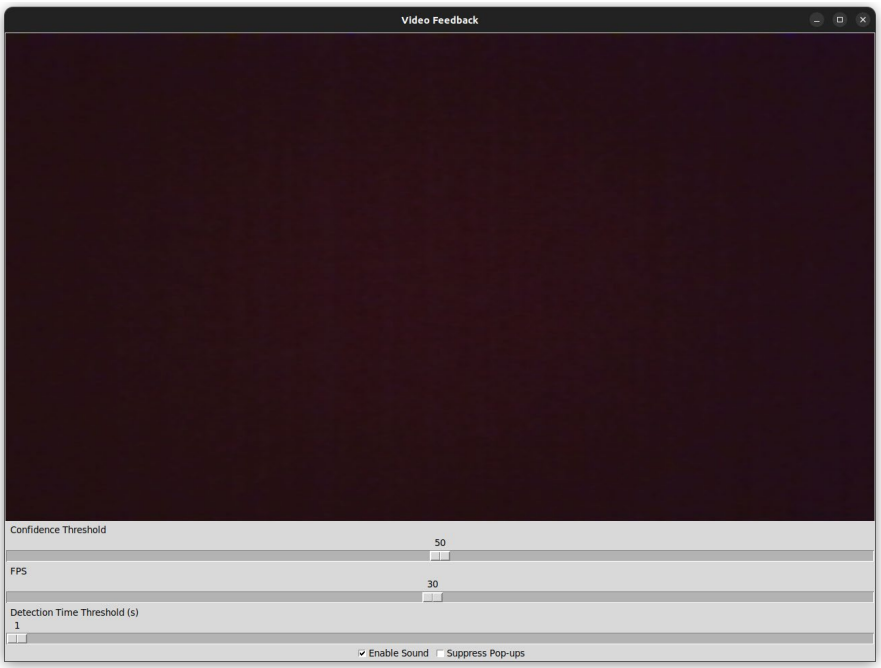

Fig. 5 - Main screen of the application during monitoring

The user also has the option to enable or disable sound alerts via a checkbox and can choose to suppress pop-up messages that appear when diseases are detected. The application is also equipped with a notification system that, once a disease is detected, sends a warning message in the form of a pop-up on the screen once the threshold time has been exceeded.

This message includes details about the type of disease detected and the time during which it has been continuously observed. The user can choose to suppress these notifications if they wish.

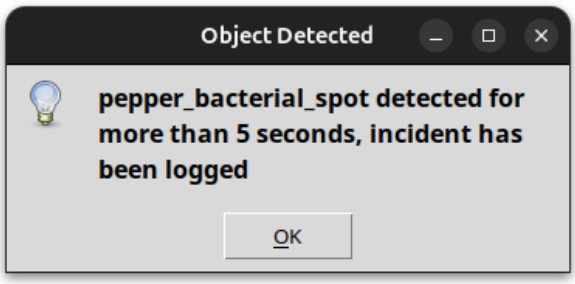

Fig. 6 - Notification pop-up with details about the detected disease and observation time

RESULTS

The results obtained from training and testing the YOLO9 models for leaf disease detection demonstrate the high efficiency of the developed system. For the model for tomato disease detection, trained on the Roboflow dataset with 10,269 images, remarkable performances were obtained in identifying the main pathologies: Early Blight, Late Blight, Septoria Leaf Spot, Leaf Miner, Leaf Mold, Mosaic Virus, Spider Mites and Yellow Leaf Curl Virus.

The evaluation on the test set showed an average accuracy (mAP@0.5) of 97% for the detection of all disease classes, with a mAP@0.5:0.95 value of 93%, indicating excellent robustness at various IoU (Intersection over Union) thresholds. The final training losses were: box loss = 0.36, class loss = 0.27, and DFL (Distribution Focal Loss) = 0.15, while the validation losses were: box loss = 0.36, class loss = 0.33, and DFL = 0.93.

The analysis of the normalized confusion matrix (Fig. 9) reveals exceptional performances per class: Leaf Miner achieved a perfect accuracy of 100%, Late Blight and Spider Mites recorded 96% and 98%, respectively, Early Blight demonstrated 96% accuracy, Mosaic Virus 95%, Leaf Mold 94%, Septoria 92%, and Yellow Leaf Curl Virus 90%. The model also showed a good ability to identify healthy leaves with 91% accuracy, essential for reducing false positives.

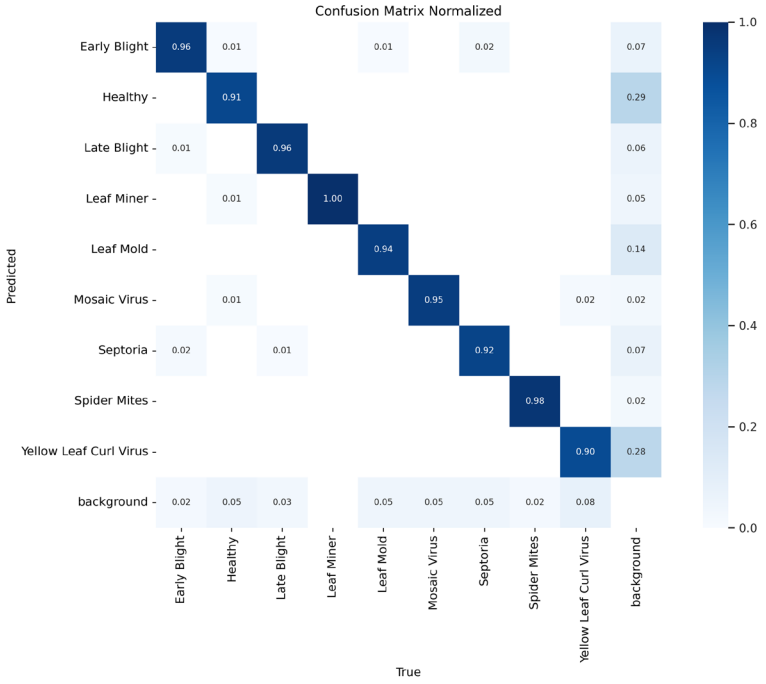

Fig. 7 - Normalized confusion matrix for tomato disease detection model

For pepper crops, the model trained on the concatenated superset of 1,256 images showed satisfactory results, with an average accuracy (mAP@0.5) of 66% and mAP@0.5:0.95 of 51%. Although these values are more moderate compared to the tomato model, they reflect the inherent challenges due to the smaller dataset and lower diversity of the training images. The final training losses were: box loss = 0.46, class loss = 0.34, and DFL = 0.23, with validation losses of: box loss = 0.46, class loss = 0.47, and DFL = 0.83.

The confusion matrix for pepper (Fig. 10) reveals differential performance between classes: Pepper Blossom End Rot was detected with the highest accuracy (99%), followed by Pepper Bacterial Spot (80%), Pepper Powdery Mildew (53%), and Pepper Frogeye Leaf Spot (49%). The main challenges were in differentiating between Pepper Frogeye Leaf Spot and Pepper Bacterial Spot, with cross-confusions of 49% for both classes, indicating significant visual similarities between these two diseases.

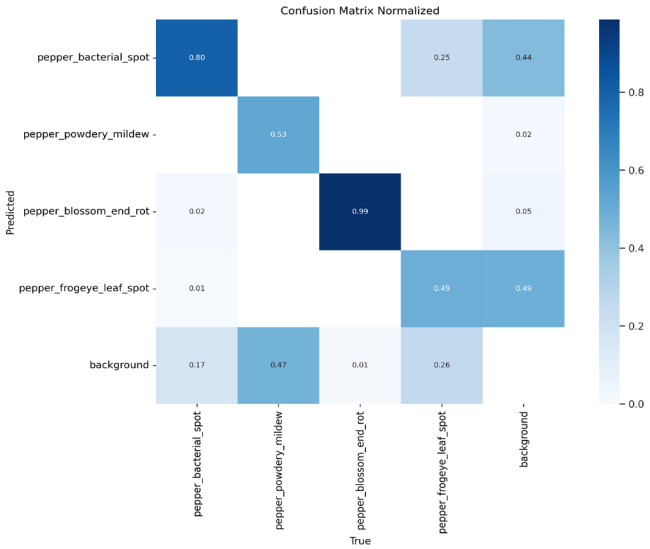

Fig. 8 - Normalized confusion matrix for tomato disease detection model

The pepper model presented greater challenges in differentiating between certain disease classes, particularly between Pepper Frogeye Leaf Spot and Pepper Bacterial Spot, where the mutual confusion was 49%, according to the confusion matrix.

This highlights the need to enrich the database for these specific classes and possibly implement additional augmentation techniques to improve discrimination between similar symptoms. However, detections for Pepper Blossom End Rot were exceptionally accurate (99%), providing a reliable tool for identifying this common disease.

The automatic incident saving functionality has been proven functional under laboratory testing conditions. The system generates detailed CSV records for each confirmed detection, including precise information on the time of the incident, the type of disease, the spatial coordinates of the affected area, and the level of confidence of the prediction.

07:20:36	pepper_bacterial_spot	pepper_bacterial_spot detected for more than 1 seconds
07:20:51	pepper_bacterial_spot	pepper_bacterial_spot detected for more than 5 seconds
07:41:23	Leaf Miner	Leaf Miner detected for more than 1 seconds
07:41:25	Leaf Miner	Leaf Miner detected for more than 1 seconds
07:44:58	pepper_bacterial_spot	pepper_bacterial_spot detected for more than 5 seconds
07:45:07	pepper_bacterial_spot	pepper_bacterial_spot detected for more than 5 seconds
07:47:57	pepper_frogeye_leaf_spot	pepper_frogeye_leaf_spot detected for more than 5 seconds, incident has been logged
07:47:58	pepper_blossom_end_rot	pepper_blossom_end_rot detected for more than 5 seconds, incident has been logged

Fig. 9 - Automatic recording of detected incidents with timestamp and technical details

Performance tests under laboratory conditions demonstrated the system's ability to process images at a constant rate of 25 fps on the specified standard hardware configuration. The average processing time for a 640x640 pixel image, including preprocessing, YOLO9 inference, and post-processing of the results, was 40-48 ms, with most of the time spent waiting for a new image to be acquired, allowing for real-time monitoring without noticeable delays.

CONCLUSIONS

This article demonstrates that the YOLO9 algorithm, integrated into a tomato and pepper leaf disease recognition application, provides fast and accurate automatic detection. The tomato model achieved high performance (up to 97% mAP), confirming the usefulness of deep learning in phytosanitary monitoring. The pepper model had more modest results (66% mAP), highlighting the need for larger and more varied datasets.

The system reduces manual inspections, detects diseases before visible symptoms appear, and allows for continuous 24/7 monitoring. Major limitations relate to data quality and hardware requirements, but the solution has high potential for practical application in greenhouses and commercial farms, contributing to the digitalization and efficiency of precision agriculture.

ACKNOWLEDGEMENT

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MODERN METHODS FOR PROCESSING FERMENTED DAIRY PRODUCTS
/
METODE MODERNE DE PROCESARE A PRODUSELOR LACTATE FERMENTATE

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Keywords: *fermented dairy products, yogurt, kefir, non-thermal technologies.*

ABSTRACT

Fermented milk products represent one of the most appreciated food categories, valued for their distinct sensory and physicochemical characteristics, as well as their health-promoting properties. The production of fermented dairy products, which began with the ancient practice of acidifying milk, has significantly increased milk's shelf life. This study provides a concise review of modern technologies used in the production of fermented milk products, with a focus on yogurt and kefir. The article presents innovative fermentation methods that improve safety, sensory quality, and shelf life, such as the Maroyaka Tannen technique and non-thermal technologies including CO_2 addition, high-pressure processing (HPP), and ultrasound technology. Additionally, equipment like the APV Cavitator and CaviMaster are explored for their efficiency in homogenization, thermal control, and the optimization of functional properties.

REZUMAT

Produsele lactate fermentate reprezintă una dintre cele mai apreciate categorii de alimente, apreciate pentru caracteristicile lor senzoriale și fizico-chimice distincte, precum și pentru proprietățile lor benefice pentru sănătate. Producția de produse lactate fermentate, care a început cu practica antică de acidificare a laptelui, a crescut semnificativ durata de valabilitate a laptelui. Acest studiu oferă o trecere în revistă concisă a tehnologiilor moderne utilizate în producția de produse lactate fermentate, cu accent pe iaurt și chefir. Articolul prezintă metode inovatoare de fermentare care îmbunătățesc siguranța, calitatea senzorială și durata de valabilitate, cum ar fi tehnica Maroyaka Tannen și tehnologiile non-termice, inclusiv adaosul de CO_2, procesarea la presiune înaltă (HPP) și tehnologia cu ultrasunete. În plus, echipamente precum APV Cavitator și CaviMaster sunt explorate pentru eficiența lor în omogenizare, control termic și optimizarea proprietăților funcționale.

INTRODUCTION

Recent advances in food science have led to the emergence of innovative methods for processing fermented dairy products, aiming to preserve their nutritional value while enhancing their sensory and functional characteristics. While traditionally, fermented milk was obtained using starter cultures at controlled temperatures modern consumer demand for milder products with a smooth texture and enhanced bioactive properties has driven the development of non-thermal technologies and adapted fermentation approaches.

According to reports, the global yogurt market has followed steady growth in recent years, with notable differences between regions and countries. In 2020, the global value was slightly over USD 90 billion, supported by large markets such as China and the United States, where consumption of functional dairy products increased in the context of the pandemic. In 2021, the market surpassed USD 95 billion, with significant contributions from Germany and France, where the tradition of yogurt consumption is strongly established. In 2022, the market reached around USD 100 billion, driven by convenient formats and drinking yogurts, with rapid expansion in India and Brazil, emerging markets with high potential (*Mordor Intelligence, 2025).* In 2023, the value approached USD 103 billion, supported by the popularity of high-protein diets, especially in the United States and the United Kingdom, where “high-protein” and “low-sugar” yogurts have become highly sought after. For 2024, the report estimated a value of USD 105.61 billion, reinforced by rising demand in China—the largest market in the Asia-Pacific region—and stable demand in Western Europe. In the medium term, by 2029, the global market is projected to reach USD 135.84 billion, with a compound annual growth rate (CAGR) of 5.16%. The Asia-Pacific region will remain the main driver of expansion, through countries such as China, India, and Japan, while mature markets in Europe (Germany, France, the

United Kingdom) and North America (the United States, Canada) will continue to dominate through innovation and a focus on probiotic and functional products (*Mordor Intelligence, 2025).*

Fig. 1 - Estimated global yogurt consumption per capita, 2017–2030
(source: Mordor Intelligence, 2025)

According to the latest report entitled *"Yogurt Market: Size, Share, Trends and Forecast by Product Type, Flavor, Distribution Channel, and Region, 2025–2033"*, the global yogurt market was valued at approximately USD 127.4 billion in 2024. Estimates indicate that it will reach USD 203.8 billion by 2033, registering a compound annual growth rate (CAGR) of around 5.4% during the period 2025–2033 (*Mordor Intelligence, 2025).*

Regarding the production technologies Maroyaka Tannen technique was developed by Hiroshi Horiuchi at Meiji and is based on reducing the dissolved oxygen content in milk and carrying out fermentation at lower temperatures than conventional ones. This favors optimal metabolic activity of lactic acid bacteria and leads to a fine texture and moderate acidity. The method gives yogurt a smooth texture and mild flavor, closely replicating the traditional Bulgarian style. Using this fermentation approach, it becomes possible to reproduce on an industrial scale the specific flavor of Bulgarian yogurt. This production method is currently applied in yogurts such as LB81 Zero-Fat Plain, Meiji Probio Yogurt R-1 Low-Fat, and others. The research was initially inspired by the technology behind Meiji Oishii Gyunyu milk, which achieved a unique taste by removing oxygen from the milk before pasteurization. The process also proceeded at a much faster pace considering the fermentation time *(Horiuchi, H., 2014).*

REVIEW OF MODERN PROCESSING TECHNOLOGIES

The Maroyaka Tannen Technique

The Maroyaka Tannen technique, developed by Hiroshi Horiuchi at Meiji, is based on reducing the dissolved oxygen content in milk and fermenting at lower than conventional temperatures. This method favors the optimal metabolic activity of lactic acid bacteria, resulting in a fine texture and moderate acidity. The technique allows for the reproduction on an industrial scale of the smooth texture and mild flavor characteristic of traditional Bulgarian yogurt *(Horiuchi, H., 2014).*

It is currently used in products such as LB81 Zero-Fat Plain and Meiji Probio Yogurt R-1 Low- Fat. The research was inspired by the unique taste achieved by removing oxygen from milk before pasteurization. This process significantly reduces fermentation time. Traditionally, yogurt is fermented at temperatures above 40°C. While traditional Bulgarian yogurt ferments at a much lower temperature, past attempts to scale this method failed due to slow fermentation and a soft curd. In the Maroyaka Tannen technique, deoxygenated milk is inoculated with Lactobacillus delbrueckii subsp. bulgaricus and Streptococcus thermophilus. Deoxygenating the milk before adding the cultures stimulates bacterial activity under low-temperature conditions, thereby reducing fermentation time and improving the yogurt's texture *(Horiuchi, H., 2014).*

Technologies Developed by SPX

Technologies from SPX, such as the APV Cavitator and CaviMaster, offer significant innovations in dairy processing. The APV Cavitator is a modular unit that uses controlled cavitation for highly efficient mixing and flameless heating, ensuring a smooth texture, uniform heating, and effective aeration. This method improves the hydration of powder ingredients and the functionalization of milk proteins and whey protein concentrate (WPC), which increases product viscosity and stability. The technology also reduces fouling, lowers costs, and increases productivity, enabling a creamy texture even in low-fat products. The new CaviMaster combines the benefits of the Cavitator and LeanCreme to facilitate the development of

innovative, low-fat yogurts with high nutritional value using whey proteins. This recombination concept supports sustainable production that is less dependent on the quality of raw milk *(SPX FLOW, 2013).*

Non-Thermal Technologies - addition of carbon dioxide

Adding CO_2 to milk lowers the pH by forming carbonic acid. While *Lactobacillus bulgaricus* is relatively tolerant to CO_2, the CO_2 produced by *Streptococcus thermophilus* stimulates the growth of *Lactobacillus bulgaricus*, as the latter requires CO_2 for cell growth. Supercritical carbon dioxide (sCO_2) is a liquid state of CO_2 achieved above a critical temperature of 31.1°C and a critical pressure of 7.4 MPa. The benefits of using sCO_2 include its low viscosity and high solubility in both the aqueous and fat phases of food materials. Its use for inactivating alkaline phosphatase and *Escherichia coli* in milk has been investigated, with one study finding that a ratio of 0.05 sCO_2:milk, at 70°C, 80 bar, and a holding time of 30 minutes, inactivated *E. coli* and 94.5% of the enzyme *(Marella, C., et al., 2015).*

High-Pressure Processing (HPP)

High-Pressure Processing (HPP) can be implemented as either a batch or a semi-continuous process. In the batch process, food is placed in a vessel filled with a pressure-transmitting liquid. The target pressure, which can range from 50 to 1000 MPa, is applied by a pump or piston and maintained for a set period before depressurization. A current application of HPP in the yogurt industry is post-packaging treatment, which inactivates yeasts and molds for up to three months and reduces *Lactobacillus bulgaricus* counts, preventing post-acidification. Research on set yogurt from HPP-processed milk showed that milk treated at 193 MPa had no disruptive effect on casein micelles or whey protein denaturation. In contrast, milk treated at 676 MPa exhibited smaller casein micelles than thermally treated milk *(Krystian M., Paul D., Szymon S. et al, 2019).*

Low-Frequency Ultrasound Technology

Ultrasound refers to sound waves with a frequency above 16 kHz. Low-frequency ultrasound (20–100 kHz) is used to modify the physical properties of products and inactivate microorganisms, while high-frequency ultrasound (20 kHz to 2 MHz) is primarily a non-destructive analytical method. Cavitation, the formation and implosion of microbubbles in liquid media, is a key mechanism of action. Low-frequency ultrasound produces high acoustic pressure, resulting in a high cavitation rate. One study found that ultrasound treatment had a homogenizing effect on milk fat globules, reducing their size *(Prosekov, A., et al., 2025).* Treatment at 90 W (20 kHz) for 10 minutes achieved a homogenization effect similar to conventional methods. Higher power levels resulted in a more uniform dispersion of smaller fat globules. This reduction in fat globule size also enhanced the milk's water-holding capacity *(Prosekov, A., et al., 2025).*

Table 1

Comparative table about the advantages and disadvantages for Maroyaka Tannen, CO_2, HPP and ultrasound

Technology	Advantages	Disadvantages	Mechanism of action
The Maroyaka Tannen	– Reduces astringent taste – Improves clarity and stability of beverages – Gentle, natural method	– Limited effect only on phenolic compounds – Extra cost for tannin extracts – May subtly alter flavor	Treatment with natural tannins (usually plant extracts) that bind proteins and polyphenols, reducing astringency and improving stability.
CO_2 (carbonation / supercritical)	– Recognized, safe method – Improves microbiological stability – Can preserve aroma and color – Supercritical CO_2 also acts as a selective solvent	– High cost (high- pressure equipment) – May slightly alter taste via acidification – Requires strict pressure control	Dissolved or supercritical CO_2 inhibits enzymes and microorganisms, lowers pH, and improves stability.
HPP (High Pressure Processing)	– Preserves color, flavor, and nutrients – Effective microbial inactivation – No additives needed	– Very high cost (complex equipment) – Does not inactivate all enzymes – Unsuitable for products with gas/air (packaging may burst)	Hydrostatic pressure (300–600 MPa) inactivates microorganisms and some enzymes without thermal treatment.
Ultrasound	– Can reduce microbial load – Enhances extraction of bioactive compounds – Versatile technology, combinable with others	– Limited effectiveness as a stand-alone method – May generate oxidation compounds – Can affect texture or flavor if not controlled	Acoustic cavitation: bubble formation and collapse generate localized temperature and pressure, disrupting microbial cells and modifying proteins/polyphenols.

DISCUSSION FINDINGS

The **Maroyaka Tannen technique** demonstrates that fermentation time can be significantly shortened by controlling dissolved oxygen levels, even at lower temperatures. The symbiotic relationship between *Lactobacillus bulgaricus* and *Streptococcus thermophilus* is essential for this process, as the deoxygenation stimulates their activity.

In the case of **HPP**, the results indicate that the treatment parameters are crucial. While high pressure at 676 MPa for 30 minutes produced a yogurt with firmness similar to that of a thermally treated one, a lower pressure (193 MPa) or a shorter duration (5 minutes) resulted in a weaker gel. Both HPP at high pressure and thermal treatment were found to alter whey proteins, which then bound to κ-casein. Furthermore, HPP-treated yogurt gels lost minimal water-holding capacity after 20 days of storage, on par with thermally treated gels.

For the **addition of CO_2,** the data shows that this method leads to a significantly higher lactic acid content after seven days of storage compared to a control sample. This supports the conclusion that pre-acidification with CO_2 can accelerate the fermentation process.

Finally, the **Low-Frequency Ultrasound** technology has proven effective in improving milk's physical properties. It has a homogenizing effect on fat globules and enhances water-holding capacity by increasing the surface area for interactions with casein. A key finding is that the beneficial effects on the gel's texture and water-holding capacity are caused by physical changes (homogenization) or heat generated during the treatment, not by the ultrasound or pressure itself. This highlights the importance of controlling the temperature during ultrasound treatment to achieve desired results.

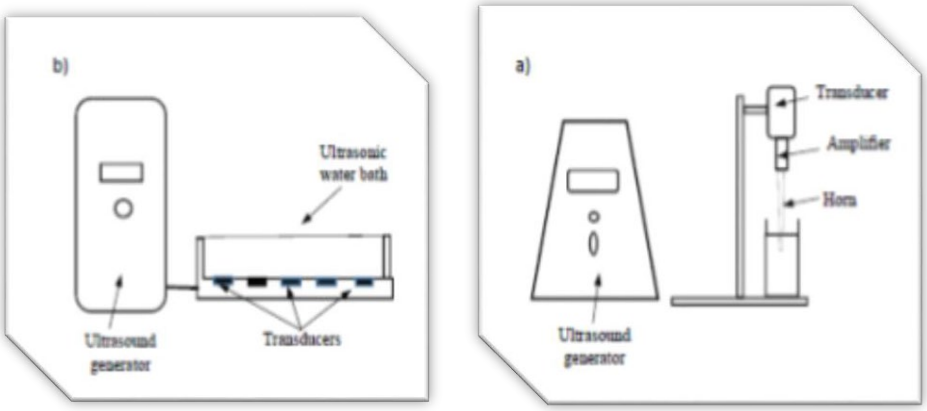

Fig. 2 - Ultrasound setup: (a) ultrasound probe; (b) ultrasonic bath
(adapted from Horiuchi, H. 2023)

During the study, the temperature was maintained at 20 or 40°C (below the denaturation temperature of whey proteins), and no whey protein denaturation was observed, indicating that any whey protein denaturation was attributed to heat generation rather than an effect of ultrasound. The resulting acid gels exhibited low firmness at these temperatures (20 and 40°C). When the temperature was maintained at 60°C, the acid gels reached a final firmness of up to 260 Pa *(Schorsch, B. C., & Haug, W., 2001).*

The costs and scalability of each technology

Regarding CO_2, the costs are relatively low because the equipment required for injection and pressure control is simple and does not involve major energy or maintenance expenses. This technology is highly scalable and can be easily integrated into existing dairy production lines. Additionally, CO_2 allows precise control of acidification and colloidal calcium phosphate solubilization, which influences gel firmness, texture, and syneresis *(Anne K. L., Tijs A.M. R., et al., 2022).*

High Pressure Processing (HPP) is a significantly more expensive technology. The equipment requires investments ranging from hundreds of thousands to millions of dollars, with considerable energy consumption and maintenance. Scalability is possible, but the high cost limits commercial adoption for small-scale production. At the molecular level, HPP partially denatures proteins and solubilizes colloidal calcium phosphate, modifying the gel network and affecting firmness and water-holding capacity *(Chawla, R., et al., 2010).*

Ultrasound has moderate costs, with equipment requirements depending on frequency, power, and batch size. Scalability is good for medium and large facilities, though process efficiency depends on the uniform distribution of ultrasound waves. Molecularly, cavitation generated by ultrasound fragments micelles,

exposes colloidal calcium phosphate, and accelerates ion transfer, resulting in more uniform and elastic gels *(Sutariya, S., Sunkesula, V., Kumar, R., & Shah, K. 2018).*

For **tannins (Maroyaka Tannen**), costs range from low to moderate, depending on the type and purity of polyphenols used, and the technology is highly scalable. Tannins can be easily incorporated into existing processes and influence gel structure through protein–polyphenol complex formation and calcium ion chelation, modulating firmness, texture, and syneresis *(Sutariya, S., Sunkesula, V., Kumar, R., & Shah, K. 2018).*

Health-promoting properties

Regarding the **health-promoting properties** discussed in the introduction, each technology influences the viability of probiotics or the formation of bioactive peptides to varying degrees. The technologies used in dairy processing not only affect texture and gelation but also have a direct impact on health benefits by influencing the viability of probiotic microorganisms and the generation of bioactive peptides *(Singh, P., et al., 2012).*

In the case of CO_2, acidification resulting from carbonic acid formation can lower the medium's pH and influence the enzymatic activity of lactic bacteria. However, CO_2 allows very fine control of pH and the acidification rate, which can protect probiotic viability if the process is properly adjusted. Additionally, moderate acidity promotes the activation of endogenous proteases from both milk and bacteria, potentially leading to the formation of bioactive peptides, such as antihypertensive or immunomodulatory peptides *(Singh, P., et al., 2012).*

High Pressure Processing (HPP) has a more complex effect on probiotics and bioactive peptides. High pressure can partially inactivate sensitive microorganisms, reducing the viability of some probiotic cultures, but certain resistant species may survive and even benefit from a more favorable environment due to Ca^{2+} release and protein structure modifications. Moreover, HPP can induce partial protein denaturation, exposing protein fragments to proteases and stimulating bioactive peptide formation, without affecting thermolabile compounds such as vitamins or unsaturated fatty acids *(Siddiqui, S. A., et al., 2024).*

Regarding **ultrasound**, cavitation and mechanical forces can affect both microflora and milk proteins. Ultrasound applied at moderate intensity can stimulate probiotic activity by increasing nutrient availability and enhancing the transfer of oxygen or ions, thereby improving viability. At the same time, micelle fragmentation and exposure of colloidal calcium phosphate can facilitate protease action, promoting the generation of bioactive peptides, while excessive exposure or high intensity may reduce the viability of sensitive bacteria *(Silva, M., et al., 2022).*

In the case of tannins **(Maroyaka Tannen**), the effects are indirect and dose-dependent. Tannins can form complexes with proteins and cations, modifying gel structure and nutrient accessibility. At moderate levels, tannins can create a protective environment for probiotics by reducing oxidative stress and safeguarding bacterial cells. Simultaneously, protein complexation can influence how proteases act on the protein matrix, potentially stimulating or modulating the formation of bioactive peptides, such as those with antioxidant or antimicrobial effects *(Ojo, M. A., et al., 2022).*

CONCLUSIONS

The Maroyaka Tannen Technique

In this technique, tannins (polyphenols) interact strongly with proteins through multiple bonds (hydrophobic interactions) and can chelate metal ions (Ca^{2+}), resulting in the formation of complexes, precipitation, or reorganization of protein networks. In parallel, they can chelate calcium ions, reducing the Ca^{2+}–phosphate bridges responsible for micellar aggregation.

The result is a different gel network: sometimes more stable and less prone to syneresis (due to additional cross-linking), and other times softer if calcium binding weakens micellar junctions. Thus, tannins can act as "modulators" of the gel's texture and firmness, depending on their dose and type. This concept for yogurt and fresh cheese categories is based on recombined powder formulations that can be integrated with liquid milk, milk concentrate, or whey components.

The use of this technology enables sustainable production, which is less dependent on the quality or availability of raw milk. The resulting products exhibit creaminess and a smooth mouthfeel, providing a solution that can be tailored to precisely meet consumer taste preferences *(Giordano, I., et al., 2022).*

Addition of carbon dioxide

Pre-acidification of milk before fermentation (at 40 °C until reaching pH 4.6) showed a linear increase in the solubilization of colloidal calcium phosphate with decreasing pre-acidification pH. The solubilized

colloidal calcium phosphate reduced the number of cross-links between it and casein within the casein micelle, thereby decreasing the number of reticulated colloidal calcium phosphates during gelation, which results in a weaker gel. Regarding the effect on the gel at the molecular level following the addition of carbon dioxide, the pH decrease caused by carbonic acid protonates the phosphate groups in colloidal calcium phosphate and the acidic residues of caseins, reducing the net charge of the micelles *(Marella, C., et al., 2015).*

In acid coagulation (yogurt), the pH decrease reduces electrostatic repulsion between micelles and promotes aggregation through hydrophobic interactions, while the amount of ionic calcium (resulting from the dissolution of colloidal calcium phosphate) can accelerate the formation of junction points between caseins, thereby producing a faster or firmer gel, but also a more contractile one (increased syneresis). In rennet coagulation, ionic calcium is essential for the formation of Ca^{2+} bridges between caseinates; the dissolution of colloidal calcium phosphate before cleavage reduces the initial structural integrity of the micelles and can alter the texture of the resulting network *(Marella, C., et al., 2015).*

High-Pressure Processing (HPP)

High-pressure treatment of milk, particularly at 676 MPa for 30 minutes, can produce yogurt structures and properties similar to those obtained through conventional thermal treatment, affecting casein micelle size and whey protein denaturation. The final effect depends on the process parameters and the initial pH of the milk. High pressure partially denatures proteins, disrupts the internal cavities of micelles, and can solubilize colloidal calcium phosphate.

High Pressure Processing can solubilize colloidal calcium phosphate, similar to acidification, releasing ionic calcium and altering micelle size and stability. As a result, aggregations may occur between whey proteins and pressure- modified caseins *(Siddiqui, S. A., et al., 2024).*

Low-Frequency Ultrasound Technology

High-pressure or ultrasound treatment of milk can improve yogurt texture and stability by reducing fat globule size and accelerating fermentation. Most of the beneficial effects on the gel are caused either by physical changes (homogenization and protein interactions) or by heat generated during the treatment, rather than by the ultrasound or pressure itself. Thus, these technologies can be used to produce firmer yogurts with improved water-holding capacity while maintaining product safety.

Cavitation generated by ultrasound produces mechanical forces and microturbulence, such as micelle fragmentation that exposes more colloidal calcium phosphate to the solution and accelerates the transfer of CO_2 into the micelle. The impact on the gel is that CO_2 can dissolve colloidal calcium phosphate more efficiently due to enhanced transport, resulting in a more uniform and elastic gel network, with faster micelle aggregation *(Prosekov, A., et al., 2025).*

Table 2

Interaction with CCP, effect on the gel, and control parameters

Technology	Interaction with CCP / Proteins	Effect on Gel	Control Parameters
The Maroyaka Tannen	Forms carbonic acid → protonates and partially dissolves CCP → releases Ca^{2+} → micelles become more prone to aggregation	Accelerates micellar aggregation; gel can be firmer or contractile; syneresis increases if dissolution is too fast	CO_2 pressure (pCO_2), temperature, injection rate, contact time
CO_2 (carbonation / supercritical)	Partial protein denaturation, CCP solubilization, redistribution of Ca^{2+} bridges, oligomer dissociation	Gel networks vary: finer, more fragile, or denser; firmness and water-holding capacity are modified	Pressure (MPa), holding time, temperature; combining with CO_2 or mild heat can modify effects
HPP (High Pressure Processing)	Cavitation → micelle fragmentation, CCP exposure; enhances ion and CO_2 transfer	Produces more uniform, elastic gels; affects porosity and aggregation kinetics	Frequency (kHz), amplitude, duration, temperature, presence of gases/particles
Ultrasound	Forms protein–polyphenol complexes; chelates Ca^{2+}, reducing micellar bridges	Modulates gel network: can increase stability or produce softer gel; affects firmness, texture, and syneresis	Type of tannin (condensed vs. hydrolyzable), dosage, timing of addition in the process

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EXTRUSION FABRICATION OF SHEEP-WOOL REINFORCED PLA/PBAT/PA BIOCOMPOSITES FOR AGRICULTURE 4.0/5.0 APPLICATIONS

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FABRICAREA PRIN EXTRUDARE A BIOCOMPOZITELOR DIN PLA/PBAT/PA RANFORSATE CU LÂNĂ DE OAIE PENTRU APLICAȚII ÎN AGRICULTURA 4.0/5.0

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ABSTRACT

Sheep wool is an abundant keratinous waste with agronomic and material potential (Alexander P., Earland C., 1952, Process for the Treatment of Keratin and Related Materials, US Patent, No. 2622036). This work presents a reproducible processing and characterization workflow to obtain extruded bio-composites using PLA/PBAT/PA ternary matrices reinforced with sheep-wool fibres (5–25 wt%) (Fodorean G., Cota C., Cioica N., Influence of rotation speed during extrusion to the properties and morphology of biopolymers blend, Acta Technica Napocensis, Series: Applied Mathematics and Mechanics nr.56/2013, vol. III, pag. 493-496, ISSN 1221-5872; Fodorean T.G., Nagy E.M., Boeru A.I., Luca L., Marica M. (2024). Biocompozit pe bază de aminoacizi proveniți din materiale proteice keratinoase și procedeu de realizare, patent request OSIM A/00754 from 28 November 2024). Processing windows, reactive extrusion dosing of wool hydrolysates, and characterization methods (FT-IR, NMR relaxometry, SEM, DSC/TGA, mechanical testing and soil-burial assays) are integrated into a complete protocol. Target applications include biodegradable mulch films, seedbed modules and sensor housings for Agriculture 4.0/5.0 (Hunter and all 2017, Agriculture în 2050: Recalibrating targets for sustainable intensification, Bioscience, 67, 386–391). Expected outcomes are improved water buffering, adjustable mechanical properties and controlled biodegradability.

REZUMAT

Lâna de ovină reprezintă un deșeu keratinos abundent cu potențial agronomic și material (Alexander P., Earland C., 1952, Process for the Treatment of Keratin and Related Materials, US Patent, No. 2622036). Lucrarea prezintă un protocol reproductibil de procesare și caracterizare pentru obținerea bio-compozitelor extrudate pe bază de matrice ternară PLA/PBAT/PA armate cu fibre din lână de ovină (5–25% din greutate) (Fodorean G., Cota C., Cioica N., Influence of rotation speed during extrusion to the properties and morphology of biopolymers blend, Acta Technica Napocensis, Series: Applied Mathematics and Mechanics nr.56/2013, ISSN 1221-5872; Fodorean T.G., Nagy E.M., Boeru A.I., Luca L., Marica M. (2024). Biocompozit pe bază de aminoacizi proveniți din materiale proteice keratinoase și procedeu de realizare, patent request OSIM A/00754 from 28 November 2024). Sunt integrate ferestrele de procesare, dozarea hidrolizatului de lână în extrudare reactivă și metodele de caracterizare (FT-IR, relaxometrie NMR, SEM, DSC/TGA, teste mecanice și studii de degradare în sol). Aplicațiile vizate includ folii biodegradabile, module de support pentru semințe și carcase pentru senzori pentru Agricultura 4.0/5.0 (Hunter and all, 2017, Agriculture în 2050: Recalibrating targets for sustainable intensification, Bioscience, 67, 386–391).

INTRODUCTION

Global wool production and textile processing generate significant wool waste *(IWTO, 2021, Wool Production, International Wool Textile Organization),* often landfilled despite valuable material and agronomic properties. Keratinous wool offers water retention, slow nutrient release and biodegradability *(Alexander P., Earland C., 1952, Process for the Treatment of Keratin and Related Materials, US Patent, No. 2622036; Bhavsar, P. S. (2020).*

Green hydrolysis of waste wool), making it a candidate reinforcement and functional additive for biodegradable polymer matrices. Combining wool with PLA/PBAT/PA blends processed by extrusion can

produce materials suitable for precision agriculture applications *(Fodorean G., Cota C., Cioica N., Influence of rotation speed during extrusion to the properties and morphology of biopolymers blend, Acta Technica Napocensis, Series: Applied Mathematics and Mechanics nr.56/2013, ISSN 1221-5872; Fodorean T.G., Nagy E.M., Boeru A.I., Luca L., Marica M. (2024).* Biocompozit pe bază de aminoacizi proveniți din materiale proteice keratinoase și procedeu de realizare, patent request OSIM A/00754 from 28 November 2024).

The paper aims to: (1) develop extrusion protocols for PLA/PBAT/PA matrices reinforced with sheep-wool fibres (5–25 water percentage); (2) define characterization methods to assess mechanical, hydric and biodegradation behaviour; (3) propose application pathways in Agriculture 4.0/5.0 for mulches, seedbed modules and transient sensor housings *(Hunter and all, 2017, Agriculture în 2050: Recalibrating targets for sustainable intensification, Bioscience, 67, 386–391; Nagy E.M., Fodorean G.,Cota C., Cioica N., Gyorgy Z., 2017, Influence of natural fibers on the mechanical properties of starch-based bioplastics PROCEEDINGS OF THE 45th INTERNATIONAL SYMPOSIUM ON AGRICULTURAL ENGINEERING "Actual Tasks on Agricultural Engineering", ISSN 1848-4425, Opatija – Croaţia; Fodorean T.G., Nagy E.M., Cioica N., Deac T., 2024, Study regarding the influence of the mechanical properties by the processing parameters in the case of ternary biopolymer blends, ISB-INMA TEH' 2024 Agricultural and Mechanical Engineering).*

MATERIALS AND METHODS

Materials: industrial-grade PLA, PBAT and a compatibilizing PA were selected as the ternary matrix (baseline 60/20/20 %). Sheep-wool feedstock was used as milled short cut fibres and alkaline hydrolysates for liquid dosing. Processing: twin-screw extrusion mixers were used with typical temperatures between 160–205 °C and rotor/screw speeds 50–100 rpm. Hydrolysates were dosed via peristaltic pump in reactive extrusion *(Nagy E.M., Fodorean T. G, Deac T., Fechete-Tutunaru L.V., 2024 - Research on wool waste processing technologies for use in agricultural crops, ISB-INMA TEH' - Agricultural and Mechanical Engineering).* Samples were granules or specimen-cast for tests *(Nagy E.M., Fodorean T.G., Nica D.V., Laza E.A., Vintila T., 2024, Researches for the physico-chemical characterization of some granular fertilizers obtained from native wool waste, in order to use them in agriculture, Scientific Papers. Series E. Land Reclamation, Earth Observation & Surveying, Environmental Engineering, Vol. XIII, 320-325; Onifade, A., Al-Sane, N., Al-Musallam, A. and Al-Zarban, S. (1998). A review: potentials for biotechnological applications of keratin-degrading microorganisms and their enzymes for nutritional improvement of feathers and other keratins as livestock feed resources. Bioresource Technology; Schwan, A., J. Herrling, and H. Zahn (1986). Characterization of internal lipids from wool. Colloid and Polymer Science).*

In order avoid excessive wool fibres degradation and to maximize interfacial bonding, was use low shear feeding and consider a mild compatibilizer (maleic anhydride grafted PLA/PBAT or a coupling agent). Pre-treatments (alkaline wash or mild hydrolysis) can increase surface polarity and potential bonding with the matrix, and allow wool to function as a nutrient carrier if loaded with hydrolysate during extrusion. The agronomic work shows protein hydrolysates obtained from wool are feasible reagents.

Formulations (recipes): B1 (60/20/20 + 5 % wool), B2 (60/20/20 + 10 % wool milled), B3 (60/20/20 + 15 % wool), B4 (60/20/20 + 10% wool + 4 % wool hydrolysate). Drying to <3% moisture before extrusion and use of mild compatibilizers (e.g., MA-grafted agents) are recommended to improve interface adhesion and dispersion.

Table 1

Formulations (recipes)

Formulation (recipe)	Biopolymers matrix (%)	Wool (%)
B1	PLA 60 / PBAT 20 / PA 20	5 (milled)
B2	PLA 60 / PBAT 20 / PA 20	10 (milled)
B3	PLA 60 / PBAT 20 / PA 20	15 (milled)
B4	PLA 60 / PBAT 20 / PA 20	10 (milled) + 4 wool hydrolysate

The processing was made by extrusion using a Collin ZK25 extruder (Fig. 1). The mixture was dosed through the extruder feed point is taken up by the two corotating screws which homogenize it and process it by shearing and heating while it is moved towards the die provided with a 7 mm diameter. The extruder has two co-rotating modular screws, with a productivity of approx. 15 kg/h, screw diameter D=25 mm, screw length: L=30xD, screw speed: max. 400 rpm.

The extruder barrel is also modular and has 6 removable and interchangeable zones, each zone having independent heating and cooling systems. The dosage of the mixture of solid components in the extruder hopper was done using a two-screw dispenser.

Fig. 1 - Collin ZK25 extrusion machine used for processing

Relating properties methods of characterization (Fig.2), a multi-technique suite is planed: FT-IR for chemical bonding; SEM/EDX for morphology and dispersion; DSC/TGA for thermal behaviour; tensile, flexural and impact tests for mechanical performance; gravimetric water uptake and dynamic nutrient-release assays for hydric function; and soil-burial compost tests for biodegradation.

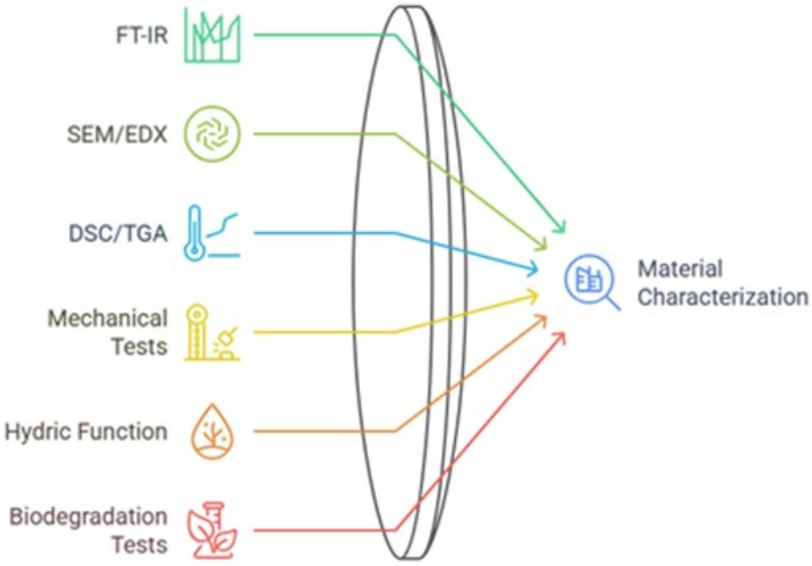

Fig. 2 - Designed protocol for establishing the properties and behaviour of the new obtained bio-composite material

On the Fig. 3 we have an example of the obtained extruded bio-composite material having wool fibers.

RESULTS

Based on literature and preliminary laboratory experiments the ternary PLA/PBAT/PA matrix is extrudable with up to around 15 % wool content without severe processing issues when rotor speeds and temperature profiles are optimized.

Wool increases water-retention and introduces porosity beneficial for mulch films and seedbed modules but may reduce tensile strength unless compatibilized. Reactive extrusion with hydrolysate

dosing enables nutrient-carrier functionality and supports agronomic compatibility with beneficial microbes.

Fig. 3 - Obtained extruded bio-composite material

Potential/planed applications case studies:

1. Smart biodegradable mulch film (25–100-500 μm): retains soil moisture via wool-induced porosity; degrades after one crop cycle; can be co-extruded with a protective top layer and inner wool-rich layer for moisture buffering. Integration of passive humidity tags enables remote monitoring of field moisture (Agriculture 4.0).
2. Seedbed modular blocks: 3D-printed or extruded thicker elements (bio-composite blocks) containing wool as nutrient and moisture reservoirs; loaded with beneficial microbial lyophilizates during extrusion for targeted early root microbiome enrichment. Compatibility of wool hydrolysate with beneficial microbes supports this route.
3. Biodegradable sensor housings: for in-soil sensor nodes that must disappear post-season, fabricated from the PLA/PBAT/PA matrix tuned for necessary strength and controlled biodegradability.

Limitations and challenges – while PLA-PBAT-PA ternary blends reinforced with sheep wool fibres offer improved biodegradability, enhanced toughness, and better thermal insulation, their integration also presents significant issues such as fibre-matrix interfacial adhesion, moisture uptake from wool, and the trade-off between stiffness and ductility. The presence of natural fibres like wool often reduces thermal stability and increases heterogeneity in mechanical behaviour across samples. Also, the complexity of blending three polymer phases (PLA, PBAT, PA) complicates achieving uniform phase dispersion, and the wool content tends to accelerate hydrolysis under humid or composting conditions.

Manufacturing new products from this bio-composite introduces further challenges: extrusion processes must be carefully optimized to prevent thermal degradation of both polymer phases and wool fibres, and high shear or temperature can damage wool keratin or cause depolymerization of the matrices. Moreover, ensuring repeatability in product quality is difficult, given variability in wool fibre properties (length, diameter, cleanness) polymer batch differences, and processing parameters; scale-up will likely require fibre pre-treatment or compatibilizers, and stringent control over blending, drying, and extrusion schedules.

CONCLUSIONS

Sheep-wool reinforced PLA/PBAT/PA bio-composites produced by extrusion present a feasible route toward biodegradable, water-buffering agricultural materials for Agriculture 4.0/5.0 applications.

The proposed processing windows, reactive extrusion dosing strategies, and characterization matrix provide a roadmap for experimental validation and scale-up. Next steps are full lab validation following the experimental plan above; results will quantify trade-offs between mechanical performance, water buffering, nutrient release kinetics, and biodegradation.

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EFFECT OF FRUITS POWDERS ADDITION ON WHEAT FLOUR DOUGH RHEOLOGICAL PROPERTIES - REVIEW

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INFLUENȚA ADAOSULUI PUDREI DE FRUCTE ASUPRA PROPRIETĂȚILOR REOLOGICE ALE ALUATULUI DIN FĂINĂ DE GRÂU - REVIEW

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Keywords: *fruit powders, wheat flour, dough, rheological properties, functional ingredients, bakery products*

ABSTRACT

In today's food industry, there is increasing interest in improving the quality of bakery products through the use of functional raw materials. The quality and safety of these products are influenced both by environmental factors and by technological innovations in the food sector. Fruit powders or flours obtained from pulp or from processing by-products such as peels and seeds are valuable sources of fiber, antioxidants, and bioactive compounds. Their incorporation enables the development of innovative products with superior nutritional profiles, enhanced functional properties, and extended shelf life. In contrast, soil contamination with heavy metals affects cereal crops through physiological and biochemical changes, reducing flour quality and threatening food safety. The addition of fruit powders such as chokeberry, sea buckthorn, currants, cranberries, rosehip, raspberry, apple, or grape can help counterbalance these adverse effects by providing antioxidants, fibers, and protective compounds. Moreover, these ingredients improve the rheological properties of dough, including hydration capacity, development time, elasticity, extensibility, and gas retention, which positively influence texture, flavour, and nutritional value. This research highlights the potential of fruit powders as a sustainable solution for obtaining functional bakery products with high added value, despite the negative effects of environmental stressors.

REZUMAT

În industria alimentară actuală există un interes tot mai mare pentru îmbunătățirea calității produselor de panificație prin utilizarea materiilor prime funcționale. Calitatea și siguranța acestor produse sunt influențate atât de factorii de mediu, cât și de inovațiile tehnologice din sectorul alimentar. Pudrele sau făinurile obținute din pulpă de fructe sau din subproduse rezultate în urma procesării, precum coji și semințe, reprezintă surse valoroase de fibre, antioxidanți și compuși bioactivi. Integrarea lor permite dezvoltarea unor produse inovatoare, cu profil nutrițional superior, proprietăți funcționale îmbunătățite și termen de valabilitate extins. În schimb, contaminarea solului cu metale grele afectează culturile de cereale prin modificări fiziologice și biochimice, reducând calitatea făinurilor și punând în pericol siguranța alimentară. Adăugarea pulberilor de fructe precum aronia, cătină, coacăze, merișoare, măcește, zmeură, mere sau struguri poate contrabalansa aceste efecte negative prin aportul de antioxidanți, fibre și compuși cu rol protector. De asemenea, aceste ingrediente îmbunătățesc proprietățile reologice ale aluatului, inclusiv capacitatea de hidratare, timpul de dezvoltare, elasticitatea, extensibilitatea și retenția de gaze, influențând pozitiv textura, aroma și valoarea nutrițională. Această direcție de cercetare evidențiază potențialul pulberilor de fructe ca soluție sustenabilă pentru obținerea unor produse de panificație funcționale și cu valoare adăugată ridicată, în ciuda efectelor negative generate de factorii de mediu.

INTRODUCTION

The bakery industry is one of the most important food production sectors, providing staple products that supply carbohydrates, proteins, dietary fiber, and bioactive compounds essential for human nutrition. In recent years, its role has expanded due to consumer demand for functional foods, health-promoting ingredients, and sustainable production systems *(Galanakis, 2021; Zarzycki et al., 2024)*.

In this context, fruit powders obtained from whole fruits or processing by-products (peels, seeds) have gained particular interest for their fiber, vitamins, polyphenols, and other bioactive compounds *(Salehi, 2020; Krakowska-Sieprawska et al., 2024)*. Unlike extracts or juices, fruit powders offer higher stability, preservation of bioactives, and easier handling, while also supporting circular economy principles by valorizing by-products *(Krakowska-Sieprawska et al., 2024)*. Meanwhile, wheat flour quality is increasingly affected by climate change, intensive agricultural practices, and environmental pollution, which alter protein, gluten, and starch content, with direct impact on dough stability and rheological behavior. The addition of fruit powders represents a promising strategy to counterbalance these effects, as their antioxidants, fibers, and bioactive compounds contribute to maintaining quality, nutritional value, and shelf life *(Han et al., 2025; Murariu et al., 2025)*.

Fruit powders also provide functional health benefits, including antioxidant and anti-inflammatory activity, cardiovascular protection, glycemic regulation, and support for gut microbiota. Fruits such as chokeberry, cranberry, blueberry, pomegranate, and sea buckthorn have been widely studied, showing improvements in nutritional and sensory profiles through natural color, flavor, and preservation properties *(Meng et al., 2019; Kasprzak-Drozd et al., 2021)*. However, their incorporation modifies dough rheology, development time, elasticity, extensibility, and gas retention, which in turn determines loaf volume, crumb structure, and texture. These changes require technological adjustments to preserve desirable quality *(Fadiji and Pathare, 2023; Cacak-Pietrzak et al., 2023; Kolesárová et al., 2025)*.

Examples such as the addition of chokeberry, sea buckthorn, or rosehip demonstrate both nutritional and functional benefits, as well as technological challenges. In the case of chokeberry, although its high anthocyanin and fiber content enhances nutritional value and extends shelf life, it significantly affects dough rheological properties *(Fadiji and Pathare, 2023; Cacak-Pietrzak et al., 2023)*. Sea buckthorn, rich in vitamins and antioxidants, provides important functional benefits but requires optimization of addition levels to avoid compromising bread texture and flavor *(Bal et al., 2011; Wang et al., 2016; Stanciu et al., 2023)*. Similarly, rosehip seed flour (Rosa canina L.) can enrich bakery products with fibers, proteins, and minerals, but it also modifies dough rheology, necessitating adjustments in formulation and processing *(Gül and Şen, 2017; Cingöz and Şahin, 2023; Sanfilippo et al., 2025)*. Moreover, currants, due to their high vitamin C and anthocyanin content, have been linked to enhanced antioxidant capacity and color stability in baked goods.

Raspberries and blackberries, rich in bioactive compounds such as fibers and polyphenols, contribute to higher nutritional value while improving natural aroma and color, whereas grapes and their by-products (pomace) are valuable sources of resveratrol and fibers, successfully applied to increase product stability, functional properties, and shelf life *(Kierońska et al., 2024; Mandache et al., 2025; Salehi, 2020)*. From a technological perspective, these challenges have prompted strategies to balance enrichment with processing performance, including optimization of addition levels, the use of functional improvers (vital gluten, enzymes), and adjustments of fermentation conditions *(Lauková et al., 2016; Murariu et al., 2025)*.

Considering the increasing demand for functional bakery products and the complexity of dough systems, understanding the mechanisms behind fruit powder-induced rheological modifications remains a research priority. In addition, fruit powders may play a dual role: enhancing nutrition while helping mitigate the negative impact of environmental contaminants on wheat-based products by improving antioxidant content, dough stability, and product safety.

MATERIALS AND METHODS

This paper is a review based on the analysis of scientific articles, conference papers, books, and relevant online publications. Sources were retrieved from international databases (Scopus, Web of Science, Google Scholar) for the period 1999-2025, with emphasis on the most recent contributions (2020-2025). Keywords used were “fruit powders,” “wheat flour,” “dough rheology,” “functional bakery products,” “antioxidants,” and “bioactive compounds.” Publications focusing on the effect of fruit powders on the rheological, nutritional, and technological properties of wheat flour dough were selected. The information was synthesized and grouped into key categories: gluten hydration, dough development time, elasticity and extensibility, gas retention, viscoelastic properties, and functional benefits.

RESULTS

The literature consistently reports that the addition of fruit powders influences both the rheological behavior of dough and the nutritional and sensory quality of bakery products. The effects depend on fruit type, chemical composition, and incorporation level, being largely driven by the interactions of fibers,

polyphenols, anthocyanins, vitamins, and the gluten network in wheat flour. In general, moderate additions (3-8%) improve the functional and nutritional profile of bread, whereas higher concentrations (>10%) often cause undesirable changes in dough volume, texture, and rheological performance *(Djeghim et al., 2021)*.

Impact of fruit powder addition on dough rheological behaviour

Existing studies show that fruit powders induce significant changes in wheat dough properties, primarily through their content of soluble and insoluble fibers, polyphenols, organic acids, and sugars *(Della Valle et al., 2022)*. Key rheological parameters affected include water absorption, dough development time, elasticity, extensibility, gas retention capacity, and viscoelastic properties, all of which directly influence bread quality.

Water absorption capacity and gluten hydration

Dough quality refers to the set of properties that determine its technological performance in the breadmaking and baking process, including softness, extensibility, stretchability, elasticity, stability, and the balance between moisture, stickiness, and dryness *(AbuDujayn et al., 2022)*. These characteristics largely depend on flour composition, especially gluten proteins (glutenin and gliadins), fiber content, hydration, and water absorption capacity, as well as on mixing, fermentation, and baking conditions.

High-quality dough must be extensible enough to expand during fermentation/proofing, but also elastic enough to retain the produced gases without tearing or becoming too rigid. Farinographic parameters, such as water absorption, dough development time, dough stability, mixing tolerance index, and degree of softening, are key indicators commonly used for evaluating dough quality. These were determined using a Farinograph Brabender (Duisburg, Germany), according to ISO 5530-1:2013 *(Lauková et al., 2016)*.

The chemical composition of commercial apple powder and fine wheat flour was reported in a previous study by *Lauková et al., (2016)*. The apple powder contained 46.1% total dietary fiber, of which 20.4% was pectin. Gluten hydration and water absorption capacity are decisive for dough functionality and loaf volume. Gluten, formed from gliadin and glutenin, provides the viscoelastic network that stabilizes gas cells. Any ingredient competing for water or altering protein interactions will therefore influence dough development and stability (*Schopf and Scherf, 2021; Almutawah et al., 2007)*.

Fruit powders enrich bakery products nutritionally, but their bioactive compounds and fibers inevitably compete with gluten for water, altering hydration dynamics *(Isaak et al., 2019).* Additions rich in insoluble fibers, such as rosehip powder or grape pomace, tend to reduce water absorption and gluten hydration capacity, leading to a less developed protein network (*Sanfilippo et al., 2025; Šporin et al., 2017)*. By contrast, powders high in soluble fibers (e.g., blackcurrant, raspberry) exert more moderate effects, retaining water in a gel-like form and contributing to a more uniform dough texture *(Alba et al., 2020; Cacak-Pietrzak et al., 2023)*.

Moreover, the high pectin content of certain fruits (citrus, apples) may increase water-holding capacity, though often accompanied by reduced gluten elasticity due to interference with protein bonding *(Sharoba et al., 2013; Mudgil, 2017)*. Other polysaccharides, such as β-glucans and arabinoxylans, redistribute water and destabilize protein structures, resulting in doughs with reduced elasticity and extensibility *(Welc-Stanowska et al., 2023)*. In the study of *Schopf and Scherf (2021)*, ten commercial vital gluten samples were analyzed to determine the factors underlying their variable baking performance.

Protein composition (gliadins and glutenins), free thiols, and disulfide bonds were quantified, and micro-baking trials were performed using both a complex bread mix and a weak wheat flour. The authors demonstrated that bread quality was not determined by protein composition, but rather by water absorption capacity, with each sample showing a distinct optimal hydration level for maximum loaf volume.

As illustrated in Figure 1, samples hydrated at or near their optimal level produced larger, well-aerated breads, while those under- or over-hydrated yielded smaller, denser loaves. This highlights that industrial baking performance can only be ensured by adjusting water addition to the hydration properties of each gluten batch, even though this practice is rarely applied.

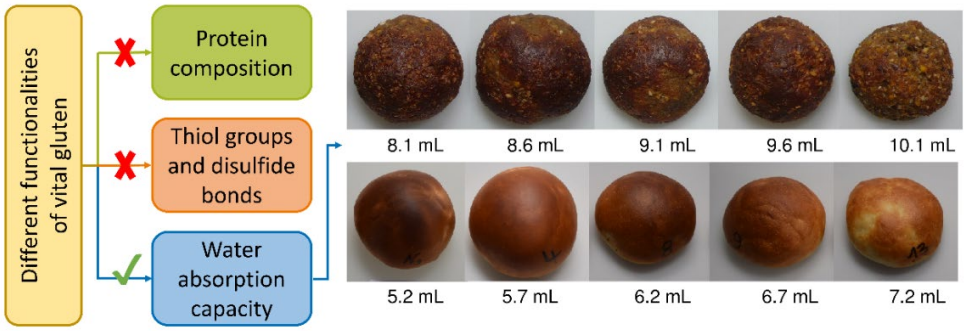

Fig. 1 - Functional performance of different vital gluten samples in breadmaking. Bread volumes varied as a consequence of differences in water absorption capacity, while protein composition and disulfide bonding were not decisive factors

(Schopf and Scherf, 2021)

Therefore, assessing the impact of fruit powders on water absorption and gluten hydration is critical for understanding dough rheology and for adjusting processing conditions to maintain both nutritional and sensory quality. A synthesis of literature findings is presented in Table 1, which summarizes the effects of different fruit powders on water absorption, gluten hydration, and baking outcomes.

Table 1

Effect of fruit powders on water absorption and gluten hydration

Fruit powder / additive	Effect on water absorption	Effect on gluten hydration	Consequences for dough / bread quality	References
Rosehip, chokeberry	Decrease (due to high insoluble fiber content)	Limit gluten hydration	Increased dough stability but reduced extensibility; lower loaf volume	*Matas et al., 2022; Cacak-Pietrzak et al., 2023*
Berries (e.g., blackcurrant, raspberry)	Moderate effect on water absorption	Partial preservation of gluten hydration	Stiffer dough with slower fermentation and reduced loaf volume; pre-hydration mitigates negative effects	*Stanciu et al., 2023; Reißner et al., 2020*
Apple powder (hydrated)	Significant increase (e.g., from ~58% to ~75%)	Extended dough development time, reduced mixing tolerance	More stable dough, but less resistant to mechanical stress	*Lauková et al., 2016*
Apple pomace (dried)	Increased water absorption	Weakened gluten network at high inclusion levels	Firmer texture of final products, lower loaf volume, impaired crumb quality	*Usman et al., 2020; Jannati et al., 2018*
Pomegranate powder	Moderate increase in water absorption	Improved cohesiveness and elasticity	Enhanced dough viscoelasticity and texture at 4-12% addition; high levels may deteriorate structure	*Zhang et al., 2023*
Sprouted wheat	Decrease (due to higher enzymatic activity, e.g., amylases and proteases)	Lower gluten index, weaker aggregation	Softer, less viscoelastic dough	*Annor et al., 2015*
β-glucans (barley, yeast)	Redistribution of water (effective decrease for gluten)	Formation of a weaker, less elastic protein network	Decreased elasticity, cohesion, and dough stability	*Welc-Stanowska et al., 2023*
Fruit/vegetable by-products (fiber-rich)	Moderate increase at low levels; decrease at high levels	Interaction with gluten proteins, limiting hydration	Good dough performance at moderate levels; impaired gluten network at higher doses	*Djeghim et al., 2021*
Technological	Decrease (salt	Salt strengthens the	May mask or amplify the	*Isaak et al., 2019*

Fruit powder / additive	Effect on water absorption	Effect on gluten hydration	Consequences for dough / bread quality	References
factors (salt, water level)	reduces water absorption)	gluten network but modifies perceived gluten strength	effects of fruit powder additions	
Spectroscopic studies on gluten hydration	Changes depending on water content	Hydration alters protein conformation	Direct impact on rheological behavior and bread volume	*Almutawah et al., 2007; Schopf and Scherf, 2021*

Table 1. Synthesis of literature findings on the effects of fruit powders and related factors on dough rheology. The table summarizes how different fruit-derived ingredients influence water absorption and gluten hydration, highlighting their technological consequences for dough handling, bread volume, and crumb quality.

Dough development time

The dough development time is defined as the interval required, during kneading, for the dough to reach the maximum consistency corresponding to the optimal development of gluten. It is one of the central parameters analyzed with the farinograph, usually reported together with stability and degree of softening *(Fig. 2)*. This parameter reflects the process of hydration and alignment of gluten proteins into a viscoelastic network capable of retaining fermentation gases *(Suprabha Raj et al., 2023)*, being recognized as a reliable indicator of flour performance *(*Oyeyinka *et al., 2023)*. From a mechanical perspective, dough development progresses through the increase in apparent viscosity under shear and extensio0n, until over-kneading leads to network degradation.

Development time thus marks the transition from the progressive accumulation of rheological properties to an apparent equilibrium state of a fully developed dough *(Zheng et al., 2000)*.

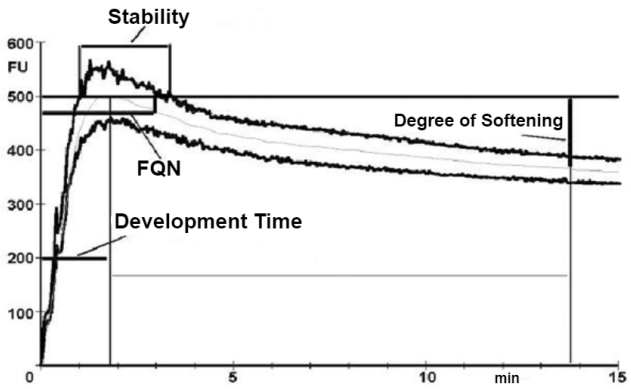

Fig. 2 - Schematic presentation of Farinograph parameters, Brabender Measurement
(Mekuria and Emire, 2015)

The presence of fibers and polyphenolic compounds retards the interactions between glutenins and gliadins, resulting in a less cohesive protein network. Consequently, the development time is often reduced as the level of functional additives increases, with the gluten network reaching maximum stability more quickly but with lower qualitative properties.

Recent studies on bread enriched with chokeberry powder and rosehip powder have reported significant decreases in development time, especially with additions above 8-10% *(Cacak-Pietrzak et al., 2023; Chochkov, 2023)*. Similar findings were reported by Murariu et al. (2025), who investigated the effect of integrating wheat flour with blueberry fruits on French-type bread.

The study showed that blueberry addition modified gluten development parameters and dough structure, reducing dough stability and mixing tolerance, while also influencing bread volume and texture. At moderate substitution levels, however, the breads were enriched with bioactive compounds, exhibited enhanced antioxidant activity, and achieved favorable sensory scores, demonstrating the potential of antioxidant-rich fruits to improve functional bakery products.

As shown in Figure 3, clear differences in appearance and structure were observed between control samples and those supplemented with 5% and 10% fruit powder, according to standardized technological protocols for French-type bread *(ISO 6820-1985; Foods, 2024)*.

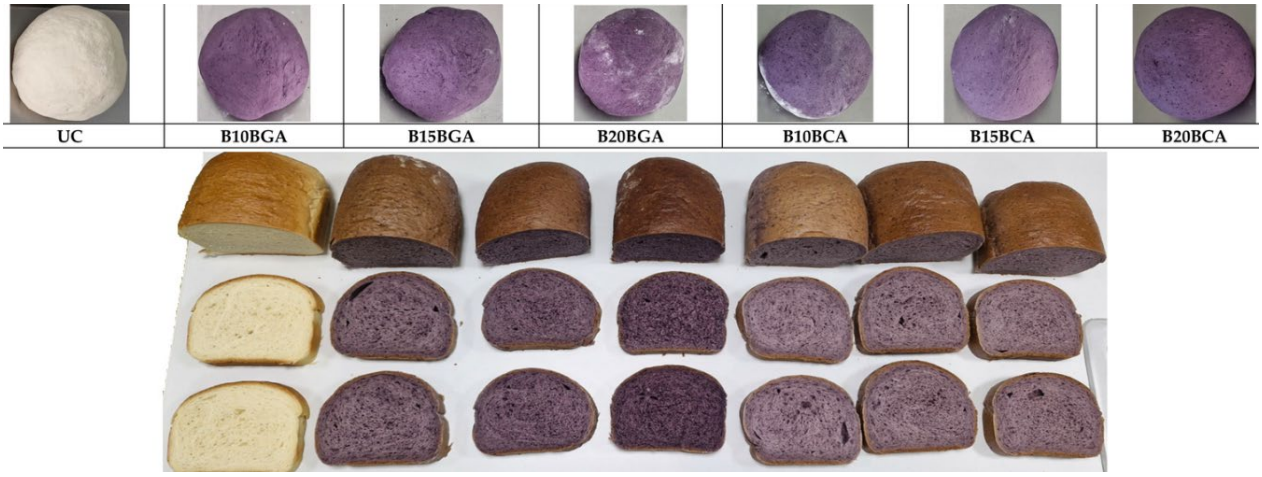

Fig. 3 - The aspect of the dough and developed bread samples obtained with different fruit powder additions (control, 5%, and 10%)
(Murariu et al., 2025)

When comparing instruments, the development time determined with the farinograph strongly correlates with Mixolab parameters, particularly with C1 development and protein weakening at C2. Thus, the profiles obtained for medium- and low-strength flours highlight clear differences in mixing kinetics and protein resistance under the combined action of kneading and controlled temperature *(Koksel et al., 2009) (Fig. 4)*.

Consistent correlations between development time, dough stability, and bread volume have been reported by *Singh et al. (2019)*, while previous studies *(Dabčević et al., 2009; Zhang and Shen, 2021)* confirmed the robustness of the parameter across various types of flours and blends.

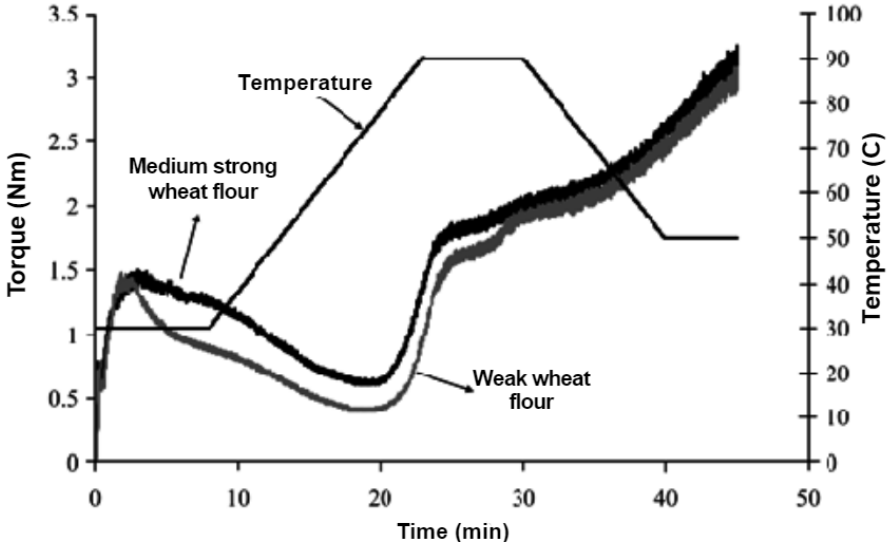

Fig. 4 - Representative Mixolab curves showing torque development for medium-strong and weak wheat flours under simultaneous mixing and controlled temperature conditions
(Koksel et al., 2009)

Agronomic factors such as heat and water stress during wheat grain filling also influence hydration kinetics and, implicitly, development time *(Lama et al., 2022)*. This sensitivity explains the widespread use of the parameter both in wheat breeding and in flour quality control and technological process adjustments (water level, kneading time, and energy).

In addition, numerous studies have highlighted the influence of composition on development time: fiber additions interfere with gluten network formation and significantly modify kneading kinetics *(Rosell et al., 2010)*, while changes in salt concentration have shown direct effects on gluten hydration and strength *(Kim et al., 2023)*. More recently, *Mahmoud et al. (2025)* showed that fiber-rich by-products, such as flour obtained from oat drink residue, significantly extend development time, with correlations confirmed through multivariate analyses.

Elasticity and extensibility

Dough elasticity and extensibility are strongly modulated by the interactions between dietary fibers and gluten proteins. In general, additions of aronia and rosehip powders increase resistance to extension and stability, but reduce extensibility, leading to stiffer doughs that are more difficult to process. This effect stems largely from polyphenol, protein interactions, which restrict the formation of flexible disulfide bonds. In contrast, softer-fleshed fruits such as raspberries and blackberries, though also polyphenol-rich, exert a less pronounced impact on extensibility due to their relatively lower insoluble fiber content *(Schefer et al., 2021)*.

Elasticity and extensibility together determine a dough's capacity to deform during processing while recovering sufficiently to maintain structural integrity, with direct consequences for sheetability, gas-cell stabilization, and final product quality. As highlighted by *Patel and Chakrabarti-Bell (2013)*, sheetability can be viewed as a practical expression of elasticity: excessive elastic recoil impedes smooth passage through rollers, whereas adequate extensibility permits thinning without rupture. Consequently, flour quality assessments often prioritize extensibility metrics over elasticity itself. Classic cereal chemistry studies have similarly shown that high resistance to extension coupled with insufficient extensibility penalizes loaf volume and processing performance *(Anderssen et al., 2004)*.

Formulation factors further modulate the elastic–viscous balance. *Catherine et al. (2012)* demonstrated that emulsifiers, hydrocolloids, and enzymes can be used to fine-tune extensibility, thereby improving both handling and volume outcomes. Chemometric analyses also support that the relative amounts and quality of gluten fractions, particularly the gliadin-to-glutenin ratio, are strong predictors of extensibility and resistance, linking molecular composition with macroscopic deformation behavior.

Empirical indices derived from instruments such as the alveograph reinforce these findings: the P/L ratio and deformation energy consistently correlate with breadmaking performance. When elasticity dominates at the expense of extensibility, doughs become harder to sheet and more prone to rupture. Conversely, balanced elasticity combined with sufficient extensibility yields smoother dough flow during processing and improved loaf quality *(Gómez et al., 2003)*.

In addition to these aspects, the incorporation of fruit and vegetable powders can significantly affect elasticity and extensibility. In the article Recent applications of powdered fruits and vegetables as novel ingredients in biscuits: a review, *Salehi (2020)* analyzed the use of dried fruit and vegetable powders such as mango, apple, carrot, pumpkin, guava, pomegranate, blueberry, or grape as innovative ingredients in biscuit production. The author showed that such additions can markedly improve the nutritional value of products through fiber, vitamins, minerals, and antioxidant compounds, while at the same time influencing rheological, physicochemical, and sensory properties.

The most notable changes occur in dough color, texture, and stability, effects primarily attributed to the fiber and polyphenol content of the powders. The conclusions emphasize that moderate incorporation of these ingredients can provide a balance between nutritional enrichment and the maintenance of acceptable sensory characteristics for consumers.

Gas retention and bread volume

Gas retention capacity represents one of the most critical determinants of bread quality, being directly associated with loaf volume, crumb porosity, and overall texture. This parameter reflects the ability of the gluten, starch viscoelastic matrix to capture and stabilize carbon dioxide generated during yeast fermentation and retained throughout proofing and baking *(Dobraszczyk and Morgenstern, 2003)*. A weakened network results in the collapse of gas bubbles, ultimately reducing bread volume.

Fruit powder incorporation into wheat-based formulations markedly influences this parameter. At high substitution levels (>5-10%), almost all fruit powders lead to reduced bread volume *(Bravo, 1999; Tong et al., 2010).* This decline arises primarily from the dilution of gluten proteins and the competition for water by insoluble dietary fibers, which hinder gluten hydration and continuity. As highlighted by *Vitrac et al., (2007)*, such fibers produce thinner gas-cell walls, thereby lowering the gas-holding capacity. Similar effects have been observed with berry pomace, where impaired fermentation and reduced loaf volume were reported unless the pomace was pre-hydrated to release water back into the system *(Reißner et al., 2020).*

Beyond the mechanical effects of gluten dilution and water competition, polyphenols and organic acids present in fruits interact with gluten proteins and starch granules, destabilizing the thin films surrounding CO_2 bubbles and weakening interfacial properties *(Lauková, 2016).* Non-starch polysaccharides, such as arabinoxylans, also interfere with gluten crosslinking, yielding fragile bubble walls *(Goesaert et al., 2005).* Likewise, β-glucans can increase dough viscosity but compromise bubble stabilization, leading to reduced volume *(Mastromatteo et al., 2011).*

Nevertheless, moderate additions (3-5%) of fruit powders can preserve loaf volume while enriching the product with bioactive compounds and dietary fibers *(Djeghim et al., 2021).* At these levels, sensory attributes such as color, aroma, and antioxidant capacity are enhanced without dramatic technological drawbacks. Examples include apple or berry pomace, which provide functional enrichment while maintaining acceptable structural quality.

Importantly, the adverse effects of fruit powders on gas retention can be mitigated through technological adjustments. Pre-hydration of pomace reduces direct competition for water, while the use of vital gluten, oxidizing agents (e.g., ascorbic acid, glucose oxidase), or polysaccharide-degrading enzymes (xylanases, cellulases) strengthens the gluten matrix and limits fiber, induced disruption. Process modifications, such as adjusting fermentation time, hydration levels, or mixing energy-can also help restore the rheological properties necessary for efficient gas entrapment *(Al-Marazeeq et al., 2024)*.

General viscoelastic properties

The incorporation of fruit powders consistently modifies the viscoelastic profile of wheat doughs, with a common observation being dough stiffening, reflected by increased values of the storage modulus (G′) and loss modulus (G″), which describe the elastic and viscous components of the system, respectively. A higher G′ indicates a more rigid, solid-like behavior, while an increase in G″ reflects stronger energy dissipation during deformation. These shifts are primarily attributed to dietary fibers and non-starch polysaccharides, which absorb water, compete with gluten proteins for hydration, and disrupt the continuity of the protein–starch network *(Meng et al., 2020; Reißner et al., 2020)*.

As a result, dough extensibility and elasticity are generally reduced, limiting the gluten network's capacity to expand and retain gas during fermentation. Studies on berry pomace and apple powders confirm that G′ and G″ values increase in small-amplitude oscillatory tests, indicating more rigid and less deformable doughs *(Lauková et al., 2016; Usman et al., 2020)*. Similar effects have been reported for arabinoxylan- and β-glucan-rich powders, where polysaccharide, protein interactions generate fragile, discontinuous networks with diminished viscoelastic recovery *(Liburdi et al., 2023; Welc-Stanowska et al., 2023)*.

At the macroscopic scale, these rheological changes translate into smaller bread volumes, denser crumb structures, and altered texture. Nevertheless, moderate additions can improve technological and nutritional attributes such as water retention, fiber enrichment, and antioxidant capacity without severely impairing dough functionality *(Zhang et al., 2023; Djeghim et al., 2021)*.

From a technological standpoint, bakers often need to compensate for the stiffening effect by adjusting hydration levels, adding functional improvers such as xylanases, cellulases, proteases, or vital gluten, or by optimizing fermentation time, mixing energy, and formulation blends. Thus, fruit powders act as a double-edged ingredient: while enriching breads with fibers, polyphenols, and bioactive compounds, they simultaneously shift dough rheology toward a stiffer, more solid-like state.

Monitoring viscoelastic parameters such as G′, G″, and tan δ (G″/G′) provides valuable insight into the balance between elasticity and viscosity, supporting formulation strategies that reconcile nutritional enhancement with desirable technological and sensory qualities *(Dobraszczyk* and *Morgenstern, 2003; Goesaert et al., 2005; Mastromatteo et al., 2011; Zykwinska et al., 2005)*.

These rheological modifications are closely related to the nutritional and technological impacts described in recent research on fruit and vegetable powders. *Salehi (2019)* reviewed the incorporation of mango, apple, carrot, pumpkin, guava, pomegranate, blueberry, and grape powders in biscuits, highlighting their ability to enrich products with fibers, vitamins, minerals, and antioxidants, while simultaneously modifying dough stability, texture, and color due to the presence of fibers and polyphenols. Similarly, *Zahid et al. (2022)* demonstrated that mango peel powder (MPP) and banana peel powder (BPP) significantly increased total phenolic content and probiotic viability in fortified yogurts but altered sensory parameters such as color, decreasing lightness (L*) from 88.42 in control samples to 59.07 with BPP.

The study of *Moraes Crizel et al., (2016)* further supports the technological relevance of fruit byproduct powders, reporting that olive powder exhibited the highest fiber content (≈53.68%), papaya powder had favorable water-holding capacity (≈8.93 g/g) and solubility (≈59.91%), while blueberry powder contained exceptionally high anthocyanin levels (≈2063.4 mg/100 g). These findings underline both the functional potential and the strong influence of bioactive compounds and fibers on dough viscoelasticity. *Ramírez-Pulido et al., (2021)* emphasized the use of fruit processing residues (peels, seeds, pulp) converted into powders rich in dietary fibers, polyphenols, and carotenoids, noting their capacity to improve antioxidant activity but also to alter sensory and functional attributes such as texture, color, and water retention capacity.

More recent contributions reaffirm these trends. *Kurćubić et al. (2025)* highlighted that fruit and vegetable powders act as functional food supplements, improving antioxidant content and nutritional value, but affecting sensory acceptance depending on concentration and formulation. *Jiang (2013)* also observed that fruit and vegetable powders can extend shelf life and retain nutritional quality, aroma, and color, but processing and storage conditions are critical for maintaining bioactive integrity.

Together, these findings corroborate that the viscoelastic modifications observed at the rheological level, dough stiffening, increased G′ and G″, reduced extensibility, are manifestations of the high dietary fiber and polyphenol contents in fruit powders. They act both as enhancers of nutritional and antioxidant properties and as disruptors of gluten hydration and network formation, confirming their role as multifunctional yet technologically challenging ingredients.

Nutritional and functional benefits of fruit powders

Fruit powders are increasingly recognized as multifunctional ingredients that combine nutritional enrichment with technological functionality in food systems. As highlighted by *Kaur and Kapoor (2001)*, fruits are valuable sources of bioactive compounds, particularly phenolics, vitamins, and minerals, that underpin their antioxidant capacity and health-promoting effects.

Converting fruits into powders preserves these compounds while extending shelf life, improving handling, and facilitating incorporation into cereal-based products. In addition, fruit and vegetable powders valorize by-products, reduce food waste, and supply fibers, phytochemicals, and natural pigments, thereby contributing to sustainable food chains *(Galanakis et al., 2020)*.

A major nutritional advantage of fruit powders lies in their high content of polyphenols and flavonoids, compounds widely documented for their antioxidant, anti-inflammatory, and antidiabetic activities. For instance, *Kunyanga et al. (2012)* reported that indigenous fruit powders markedly increase radical-scavenging activity, while *Zhangping Liao et al., (2017)* emphasized their role in glycemic regulation and oxidative stress reduction. Powders derived from tropical fruits such as durian also provide bioactive compounds associated with immune support, cardiovascular health, and improved digestion *(ChenLang Bio, 2023)*.

Beyond their nutritional profile, fruit powders deliver functional attributes relevant to food formulation. Drying methods, including spray-drying and freeze-drying, influence the retention of antioxidants and fibers, as well as solubility and powder stability *(Carrasco-Castilla et al., 2012)*. According to *Sagar and Kumar (2010)*, fruit powders act as natural stabilizers, color enhancers, and flavoring agents, thereby improving both technological and sensory performance. Their prebiotic potential has also been highlighted, with studies showing that fermentable fibers and oligosaccharides present in fruit powders stimulate beneficial gut microbiota *(Fan and Roos, 2019)*.

From a functional food perspective, incorporating fruit powders into breads, snacks, and beverages enhances nutritional density by increasing levels of dietary fiber, vitamins C and E, carotenoids, and phenolic acids. At the same time, they raise consumer appeal through attractive color, flavor, and aroma *(Giri and Mangaraj, 2012; Rivero-Pino et al., 2023)*. Furthermore, *Savaş and Demir, (2025)* demonstrated that fruit powders can act as natural alternatives to synthetic additives by contributing to oxidative stability, microbial safety, and textural improvements.

Overall, the scientific literature consistently demonstrates that fruit powders represent an efficient tool for the development of functional products. They meet consumer demand for healthy, sustainable, and sensorially attractive foods. Successful application, however, depends on the careful choice of fruit source, processing technology, and incorporation level, in order to preserve bioactive compounds while maintaining desirable rheological and technological properties.

Beyond nutritional enrichment, fruit powders may also play a compensatory role in dough systems affected by environmental stressors. Studies have shown that heavy metal contamination and environmental pollutants can impair protein functionality and gluten quality, reducing dough stability. The addition of fruit powders, through their antioxidants and fibers, may help counteract these negative effects, supporting gluten hydration, improving rheological behavior, and maintaining product safety.

Table 2 provides a comparative summary of the main studies on fruit powder supplementation in breadmaking, highlighting the typical levels of addition, their impact on bread volume, and the main rheological effects observed. This synthesis complements the narrative review by allowing a quick comparison across fruit types.

Table 2

Comparative effects of fruit powders on bread dough and bread quality

Fruit / By-product	Percentage used (%)	Effect on bread volume	Main rheological effects
Apple (powder / pomace)	5-15	Moderate decrease (>10%) at higher levels	Increases water absorption, decreases gluten elasticity
Sea buckthorn	2-10	Slight decrease, but improves nutritional value	Reduces dough development time, increases dough firmness
Aronia (black chokeberry)	2-8	Significant decrease (>15%)	Decreases extensibility, increases dough tenacity
Rosehip	3-10	Moderate decrease, but acceptable sensorially	Reduces dough stability, increases viscosity
Blackcurrant	2-6	Small decrease, tolerable	Improves gas retention, slightly decreases elasticity
Mixed berry fruits (lyophilized)	2-5	Slight decrease, compensated by enzyme addition	Reduces farinograph stability, increases dough hydration
Prune powder	5-10	Moderate decrease, still accepted by consumers	Reduces dough elasticity, increases viscosity

The role of environmental factors and contaminants on the quality of flour and dough

Flour and dough quality are shaped not only by intrinsic compositional and genetic factors, but also by environmental influences and potential contaminants encountered during cultivation, processing, and storage.

From an environmental perspective, the study by *Mikhaylenko et al. (2000)* demonstrated that wheat growing conditions have a decisive effect on flour composition, dough rheology, and baking quality. In Washington State, wheat cultivated in Lind (semi-arid) exhibited higher protein content, superior micro-SDS sedimentation values, and higher water absorption compared with Fairfield (high-rainfall). These differences translated into greater bread volumes for hard wheat grown in Lind, but larger biscuit diameters for soft wheat from Fairfield. Similarly, *Peña (2002)* highlighted the interaction between genetic background and environment, showing that breeding programs may enhance gluten quality and protein composition, but climatic and soil factors can significantly offset or modify these gains, underscoring the need for testing under diverse conditions.

Expanding this view, *Filip et al. (2023)* provided a comprehensive overview of the factors that determine the functional quality of common wheat (*Triticum aestivum L.*). Their review emphasizes that the interplay between genetic factors (protein fractions, gluten composition, enzymatic activity), environmental stresses (temperature, water availability, soil quality), and processing conditions collectively shape dough rheology and baking performance. The authors underline that even small variations in asparagine content, starch properties, or gluten protein distribution can significantly influence technological outcomes such as loaf volume, dough stability, and extensibility, reinforcing the importance of integrated genetic–environmental assessments.

Beyond agronomic conditions, environmental and technological factors can also introduce contaminants. *Maher et al. (2022)* investigated chemical contaminants in bread, identifying acrylamide, furans, polycyclic aromatic amines, 3-monochloropropanediol esters (3-MCPDE), glycidyl esters, as well as natural contaminants such as mycotoxins, heavy metals, and pesticide residues. Acrylamide levels were reported to range from tens to hundreds of µg/kg, with crust containing up to ~80 µg/kg when baked at 270 °C for 15 minutes. Similarly, 3-MCPDE concentrations of ~120 µg/kg and mycotoxin levels exceeding permissible limits were observed, stressing the importance of rigorous monitoring of raw materials and processing conditions.

Complementing this, *Varzakas (2016)* emphasized that acrylamide formation, mycotoxin contamination, and other safety risks in wheat products require the integration of advanced analytical methods (e.g., near-infrared spectroscopy) alongside strict quality controls across the processing chain. In line with this, the study *"The role of flours and leavening systems on the formation of acrylamide in the technological process of baked products: Case studies of bread and biscuits"* by *Marianelli et al. (2025)* investigated how flour type and leavening systems influence acrylamide formation in bread and biscuits. Their aim was to identify natural mitigation strategies without compromising product quality.

They examined different wheat flours and leavening systems (e.g., yeast vs. alternative agents) in combination with technological parameters such as baking temperature and time, as well as the levels of

reducing sugars and asparagine, the main Maillard reaction precursors leading to acrylamide. The study showed that flour selection, combined with leavening system choice and adjustments in baking conditions, can significantly reduce acrylamide formation in bakery products. Their findings suggest that low-asparagine flours and leavening systems that limit the accumulation of reducing sugars before baking are promising strategies for controlling acrylamide levels.

Microbiological and fungal contamination further complicates flour and dough safety. *Sami et al. (2020)* reported microbial loads from 240 samples (flour, dough, bread) collected in Isfahan, Iran. Total bacterial counts ranged from 2.83 ± 0.99 to 6.43 ± 1.12 log cfu/g, while molds varied between 0.00 ± 0.00 and 1.63 ± 0.63 log cfu/g. Bulk breads exhibited higher bacterial counts, whereas flat breads were more susceptible to molds, with species including *Penicillium* (24.4%), *Cladosporium* (20.1%), *Mucor* (20.1%), *Aspergillus* (19.0%), and *Alternaria* (3.8%).

Although levels remained below Iranian legal limits, the high consumption of bread highlights the need for continuous microbial surveillance.

In addition to chemical and microbial hazards, bakery products are vulnerable to physical contaminants. *Mutlu (2025)* reviewed the occurrence of foreign objects such as glass, metal, and plastic fragments, as well as insect and pest residues, arising during packaging, storage, and handling. The study underlined the necessity of preventive measures including visual inspections, storage monitoring, supply chain verification, and good manufacturing practices to safeguard consumer health.

Altogether, these studies converge on the notion that wheat flour and dough quality cannot be evaluated solely through compositional and rheological parameters. Environmental factors shape protein content, gluten functionality, and end-product performance *(Mikhaylenko et al., 2000; Peña, 2002; Filip et al., 2023)*, while chemical, microbial, and physical contaminants *(Maher et al., 2022; Sami et al., 2020; Mutlu, 2025; Varzakas, 2016; Marianelli et al., 2025)* pose safety and technological challenges.

Effective management therefore requires an integrated approach, breeding for resilience, cultivating under optimal agro-ecological conditions, applying strict processing controls, and implementing advanced monitoring technologies. Such strategies enable the simultaneous pursuit of high-quality and safe wheat-based products.

CONCLUSIONS

The integration of fruit powders into wheat flour dough represents a promising strategy for the development of functional bakery products with enhanced nutritional and technological properties. Scientific evidence shows that moderate additions (3-8%) of fruit powders improve fiber, antioxidant, and bioactive content, while maintaining acceptable dough rheology and bread quality. However, higher levels (>10%) often compromise gluten hydration, extensibility, and gas retention, leading to reduced loaf volume and altered texture.

The variability of effects depends strongly on fruit type, composition, and processing conditions, which highlights the need for optimized formulations and the use of technological improvers (enzymes, vital gluten, pre-hydration techniques). From a sustainability perspective, fruit powders valorise processing by-products, reduce waste, and provide natural alternatives to synthetic additives, while also contributing to food security in the context of environmental stressors and soil contamination.

Future research should focus on refining processing strategies, identifying optimal incorporation levels, and exploring consumer acceptance, to fully exploit the potential of fruit powders in next-generation bakery products.

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OBTAINING FORTIFIED WINES WITH GRAPE POMACE BIOCOMPOUNDS OBTAINED BY MAE EXTRACTION METHOD

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OBȚINEREA VINURILOR FORTIFIATE CU BIOCOMPUȘI DIN TESCOVINĂ OBȚINUȚI PRIN METODA DE EXTRACȚIE MAE

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ABSTRACT

In order to encourage the development of the sustainable food system in the wine industry, it is necessary to recover and reuse winemaking by-products such as pomace. The research carried out in this article provides compelling evidence on the prospects of using marc as an abundant source of bioactive chemicals for the creation of new functional ingredients, such as fortified wine with bioactive compounds from marc. The pomace being one of the most important waste results of winemaking, it has been subject to research with very good results in ingredients with high potential of functional bioingredients. The pomace was subjected to drying by the microwave method and followed by shredding. In order to extract the active biocompounds, the flour from the pomace from red grapes was subjected to MAE microwave extraction, and the extracts (1:10) were used to fortify the wine, with 50 ml of extract per litter of wine. Our research has been carried out on seven varieties of wine and the pomace from Stefanesti and Murfatlar wine centres in the 2023 production year. The active biocompounds in the red wine were assessed in parallel with the fortified 5% wine. The active component analysis (PCA) of the pomace has been evaluated using XLSTAST. Correlation values were evaluated using Pearson correlation. Differences in $p < 0.05$ were considered significant.

REZUMAT

Pentru a încuraja dezvoltarea sistemului alimentar durabil în industria vinicolă este necesar de a recupera și reutiliza subprodusele de vinificație, cum ar fi tescovina. Cercetările realizate în cadrul acestui articol oferă dovezi convingătoare asupra perspective utilizării tescovinei ca sursă abundentă de substanțe chimice bioactive pentru crearea de noi ingrediente funcționale, cum ar fi vinul fortifiat cu compuși bioactivi din tescovină. Tescovina fiind unul din cele mai importante deșeuri rezultate vinificării, ea a fost supusă cercetărilor având rezultate foarte bune în ingredientele cu potential ridicat de bioingrediente funcționale. Tescovina a fost supusă uscării prin metoda microundelor și urmată de mărunțirea. Pentru a extrage biocompușii active, făina din tescovina din struguri roșii a fost supusă extracției cu microunde MAE, iar extractele (1:10) s-au folosit la fortifierea vinului, cu 50 ml de extract la un litru de vin. Cercetările noastre s-au realizat pe șapte soiuri de vin și tescovină din centrele viticole Ștefănești și Murfatlar anul de producție 2023. S-au evaluat biocompușii activi din vinul martor în paralel cu vinul fortifiat 5%. Analiza activă a componentelor (APC) a tescovinei a fost evaluată utilizând XLSTAST. Valorile de corelație au fost evaluate utilizând corelația Pearson. Diferenţele la $p < 0,05$ au fost considerate semnificative.

INTRODUCTION

Currently, humanity faces one of the great challenges of the century, namely achieving a balance between economic development and environmental protection *(Diaconu, 2022).* This challenge is known as sustainability or achieving sustainable agriculture *(Diaconu, 2022).* The achievement of sustainable

viticulture and wine-making, as well as the methods to be applied to achieve sustainability, are confusing to both winegrower and winemakers companies and consumers *(Baiano, 2021; Szolnoki, 2011).* In order to define the sustainability concept applied to viticulture and wine production, both the International Organisation of Vine and Wine (OIV) have developed methodologies for sustainable wine growing (OIV 2008) and the Global Principles of Sustainability of the Wine Sector *(Diaconu, 2022; OIV, 2021; FIVS, 2016).*

According to the OIV (2021), sustainable viticulture is a "global strategy on the scale of grape production and processing systems, which at the same time incorporates the economic sustainability of structures and territories, producing quality products, taking into account the precision requirements in sustainable viticulture, environmental risks, product safety and consumer health *(Diaconu, 2022; OIV, 2021).*

The main environmental issues are: land use, water management, energy management, the use of chemicals in vine and wine treatments, waste generation, leading to greenhouse gas emissions *(Montalvo-Falcón, 2023; Diaconu, 2022; OIV, 2021)*. Viticulture, as with other types of agriculture, makes extensive use of pesticides having an important effect on the environment *(Montalvo-Falcón, 2023; Springmann, 2018).* In most vineyards around the world, technologies conventional viticulture use synthetic herbicides on soil for weeds and pesticides to control diseases and insects harmful to vines *(Montalvo-Falcón, 2023; Dumitriu, 2021).* According to Gilinsky *(Dumitriu, 2021; Gilinsky, 2016)*, by achieving sustainable agriculture in the wine sector, future generations will benefit from it *(Baiano, 2021; Dumitriu, 2021; Gilinsky, 2016).*

In the wine industry, most of the waste generated by the winemaking process is organic in nature, which means that it can be reintroduced into the natural circuit *(Diaconu, 2022).* In recent decades, economic and environmental problems have increased concerns about the high volume of waste generated in the food industries. In this respect, one of the current challenges is framing such waste as „by-products" that can be reprocessed, aiming to reduce their negative impact, as well as obtaining high benefit materials *(Caldas, 2018).*

The wine industry generates a large amount of residues, which are generally used as organic fertilizer for land or for animal feed *(Rivera, 2021).* In the wine industry, most of the waste generated by the winemaking process is organic in nature, which means that it can be reintroduced into the natural circuit *(Diaconu, 2022).*

Due to its antioxidant rich composition, the use of grape marc has numerous benefits for human health, reducing the risk of developing chronic diseases such as cancer, diabetes, inflammatory and cardiovascular diseases *(Yu, 2013)*. In Europe, many countries have begun to capitalize on winemaking waste by obtaining various valuable products for the pharmaceutical, cosmetic, food and not only industries *(Diaconu, 2022; Yu, 2013)*.

Consequently, grape pomace is considered a valuable source of phytochemicals that can be recovered in the form of functional compounds or extracts for the pharmaceutical, cosmetic and food industries. In this way, the recovery of phenolic substances from grape by-products in the wine industry has attracted increasing attention in recent years. According to the current assessments 1 kg of grape marc is generated for obtaining each 6 L of wine *(Spinei, 2021, Dávila, 2017; Mendes, 2013).*

One tonne of grape marc contains 425 kg of grape skins, 225 kg of grape seeds, 249 kg of bunch and other minor constituents *(Spinei, 2021).* Grape seed accounts for about 15% of the solid waste produced in wine *(Luque-Rodríguez, 2005),* and depending on the grape variety, the seeds are between 2% and 6% by weight of the grapes and 1% to 4% by weight of the grapes. Dried pomace seeds contain 40-65% and have an oil content of 12-22% *(Passos, 2009).* Modern techniques have demonstrated their suitability for extracting bioactive compounds by obtaining the recovery of bioactive compounds similar to or better than conventional methods *(Onache 2023; Yammine, 2020; Ahmad, 2011)*.

Therefore, it is necessary to have effective and durable extraction technologies in order to achieve a good recovery of compounds. There are many factors that influence the extraction efficiency, such as: extraction method, solvent type and concentration, temperature and extraction time *(Ahmad, 2011).* Unlike traditional extraction methods such as maceration or percolation, which require long periods of time and large amounts of solvent *(Tellez-Robles, 2024),* MAE allows for rapid and efficient extraction due to the ability of microwaves to directly heat polar molecules from the extraction material and solvent *(da Rocha, 2021; Bagade, 2019)*. This direct and uniform heating significantly reduces the processing time and at the same time improves the yield and quality of the extract obtained.

Microwave assisted extraction (MAE) is an advanced technique that uses electromagnetic radiation to facilitate and optimize the extraction process of active compounds from various materials, such as plants, food, or even industrial waste *(Bagade, 2019)*. MAE represents a significant improvement in the field of

extraction techniques, providing an optimal balance between efficiency, durability and quality of the final product *(da Rocha, 2021).*

In this article, the microwave-assisted extraction method (MAE) was used on 7 varieties of marc obtained in the 2023 production year from two wine-growing areas. With these extracts, wines obtained in the same year of production, 2023, were fortified. The wines were fortified with 50 ml of extract per 1 litter of wine.

MATERIALS AND METHODS

Chemicals and Reagents

Ethanol (pharmaceutical), Folin–Ciocalteu phenol reagent, radical scavenging assay reagents DPPH, -6-hydroxy-2,5,7,8- tetramethyl-2- carboxylic acid (Trolox) were purchased from obtained from Alfa Aesar (ThermoFisher GmbH Kandel, 76870 Kandel, Germany). All solvents were of HPLC quality, and all chemicals were of analytical grade (>99%). Analytical standards (gallic acid, abscisic acid, p-coumaric acid, caffeic acid, 3,4-dihidroxibenzoic acid, 4-hidroxibenzoic acid, shkimic acid, chlorogenic acid, siringic acid, azelaic acid, elagic acid, 2,5-dihydroxybenzoic acid, t-resveratrol, (+)-catechin, (-)–epicatechin, oenina, polidatin, t-polidatin, quercetin) from Sigmainheim.

Raw material

Grape pomace (*Vitis vinifera* varieties 'Cabernet Sauvignon', 'Burgund', 'Pinot Noir' and 'Merlot') was collected from the winery in INCDBH Stefanesti and from the SCDVV Murfatlar winery ('Mamaia', 'Pinot Noir' and 'Băbească Neagra'), the harvest 2023. The grape pomace samples were frozen and stored before the analysis. The grape pomace was dried at 45 ◦C for 5 minutes at tunnel microwave drying tape JW-MW-6 KW *(Onache, 2022)*. The grape pomace samples before drying had humidity between 85-75%, and after drying they reached between 5-8%, after which the samples were shredded using the mill with Fritsch Pulverisetti 16 hammers.

Extraction Procedures

Microwave-assisted extraction (MAE) was performed using the NEOS GR system with the following parameters: 10 g pomace/100 ml solvent (alchool), 10 minutes extraction time, power delivered in the environment 330 W. To obtain the targeted extractive fraction (polyphenols), a solvent based on distilled water and pharmaceutical ethyl alcohol (10:100 v/v) was used. With these extracts were fortified wines obtained in the same year of production 2023. The wines were fortified with 50 ml of extract per 1 litter of wine.

Analytical Investigations

Quantitative UV-Vis Spectrophotometric Determinations. In order to investigate the bioactive characteristics from wine and fortified wines were determined: total polyphenols compounds - TPC (mgGAE/L), catechins – TC (mg/L), tannins - TT (mg/L), polymerized tannins – TPT (mg/L) Total anthocianins - TA (mg/L); antioxidant activity (AA) expressed as mmol TE/L. The total polyphenolic compound content (TPC) were determined by Folin-Ciocaltu method, the absorbance was measured with Analytik Jena Specord 205 UV/VIS spectrophotometer at 765 nm and data were expressed as gallic acid equivalent (GAE)·per mg/l for sample *(Onache, 2022; Vignoli, 1960).*

Total anthocyanins were evaluated as reported by Ribereau-Gayon in 1965, the absorbance at 520 nm was read with Analytik Jena Specord 205 UV/VIS spectrophotometer, and results were expressed as mg/l *(Onache, 2023).* Catechins, monomer flavanolic units, were determined with the method by which the reaction of catechins with vanillin assay *(Onache, 2022)* (1% alchohol solution).

The absorbance was measured with Analytik Jena Specord 205 UV/VIS spectrophometer at 500 nm. Tannins have been determined by the leukocytanidins (LA) method, based on the property of tannins to transform on hot (100°C) and strongly acidic (concentrated HCl) environment into cyanidin, which is red in color *(Onache, 2023; Onache, 2022).* The optical density at a wavelength of 550 nm is directly proportional to the concentration of tannins. The evaluation of the antioxidant activity was carried out by testing free radical scavenger property. The antioxidant activity of the extracts was measured in terms of hydrogen-donating or radical-scavenging ability by means of the radical 2,2-diphenyl-1-picrylhydrazyl (DPPH•), according to a the method described by Sanchez-Moreno et al. (1999). The reaction mixtures were shaken and incubated for 45 min in the dark at room temperature *(Onache, 2022; Sanchez-Moreno et al., 1999).* The absorbance was read at 517 nm using the AnalytikJena Specord 205 UV/VIS spectrophotometer. *Polyphenolic Profile by UHPLC-HRMS.* The quantitative analysis of individual polyphenols (phenolic acids, flavonoids, and stilbens) was performed by UHPLC–ESI/HRMS (ultra-high-performance liquid chroma-

tography electrospray ionization tandem mass spectrometry) using a high-resolution Q Exactive mass spectrometer™ Focus Hybrid Quadrupole—OrbiTrap equipped with HESI, coupled to a high-performance liquid chromatograph UltiMate 3000 UHPLC (Thermo Fisher Scientific, City, State, Country).

Wine Samples

The wine was obtained from the winemaking of the 7 varieties from which the grape pomace resulted, in the same year of production, 2023. The wine was enriched with 5% extract from the grape pomace of each variety. (Stefanesti wine-centre: Burgund, Cabernet Sauvignon, Pinot Noir, Merlot and Murfatlar wine-centre: Babeasca Neagra, Mamaia, Pinot Noir).

RESULTS

Phytochemicals content of MAE extract, wine and fortified wine

Table 1 shows the results of polyphenolic compounds in the pomace extracts of the 7 grape varieties obtained by the MAE method. Total polyphenols and anthocyanins in the extracts are highlighted according to the antioxidant activity of the pomace. It is noted that the extracts have a very low content of anthocyanins, by fermenting the wine on the breastbone and by the treatments suffered by the grape pomace, most anthocyanins are destroyed. The concentration of biocompounds in the pomace was expressed in g per 100mg pomace (dry matter - DM). As observed quantities of anthocyanins after microwave extraction is reduced. The lowest amount of anthocyanins is observed in Babeasca Neagra from Murfatlar (36.108 mg/100g DM), and the highest at Pinot Noir from Stefanesti (266.175 mg/100g DM). Different from anthocyanins are found total polyphenols in very high concentrations. The highest value of PFT is found in the Burgund variety from Stefanesti (2198.7 mg GAE/100g DM), and the lowest in all the Badeasca Neagra from Murfatlar variety (1523.7mg GAE/100g DM). The concentration of total polyenols is in the same range as at (Yammine, 2020), where the total content of polyphenolic compounds varies from 0.59 ± 0.05 to 3.66 ± 0.19 g gallic acid GA/100 g dry matter for Cabernet Franc, Merlot, Pinot Noir (6.070 g/100 g DM).

Table 1

Total polyphenolic biocompound content of tescovina extract obtained by MAE method

Varieties	TPF mg GAE/100mg	TA mg/100 g	TC mg/100 g	TT mg/100g	TPT, mg/100 g	AA, mmol TE/g
M_St MAE	1926.2	57.458	3.93	73.37	0.0536	206.20
CS_St MAE	1779.9	121.217	4.11	61.33	0.0669	244.62
B_St MAE	2198.7	110.658	6.10	100.58	0.0607	120.85
PN_St MAE	1588.4	266.175	5.33	224.09	0.0238	353.17
M_Mf MAE	1651.6	105.525	3.62	69.81	0.0518	104.91
BN_Mf MAE	1523.7	36.108	2.42	38.94	0.0623	90.04
CS_Mf MAE	1530.7	57.283	3.99	71.02	0.0562	74.81
PN_Mf MAE	1543.8	76.242	4.32	105.61	0.0409	164.76

The polyphenolic profile of extracts (Table 2) made by UHPLC-HRMS is shown below.

Table 2 presents the results obtained from grape pomace extracts using MAE method, for all the compounds found. Flavonols are found in fresh grape pomace, but degrade as they undergo treatments, drying and extraction with organic solvents. The catechins are between 9.63 mg/L (MM-Mf_MAE) and 181.03 mg/L (PN_M_MAE).

Table 2

Individual phenolic compounds of pomace extracts obtained by MAE method

Extracts, mg/L	B_St_MAE	CS_St_MAE	M_St_MAE	PN_St_MAE	BN-Mf_MAE	CS-Mf_MAE	MM-Mf_MAE	PN-Mf_MAE
SHK	33.84	15.97	24.77	69.65	54.67	24.94	91.57	26.35
GAL	65.08	28.30	31.85	64.04	124.06	77.86	107.91	23.42
3,4-DHBA	11.04	2.74	3.11	17.03	24.90	17.99	44.53	2.7
2,5-DHB	0.32	0.09	0.23	1.19	1.65	0.00	2.76	0.1
4-HDB	2.11	0.95	0.77	2.75	3.47	0.00	3.79	0.71
CAT	107.31	39.72	125.93	95.82	46.70	25.62	9.63	181.03
CFA	1.08	0.99	0.31	0.47	0.24	1.23	1.15	0.39
ECAT	21.96	8.07	24.23	33.83	15.55	6.68	3.50	56.14
SYR	84.21	119.63	57.58	265.32	373.62	597.08	217.89	64.84
p-CUM	1.26	0.82	1.03	0.88	2.05	1.13	4.58	0.53

polidatin	0.85	0.83	0.66	1.12	0.83	0.61	0.59	0.59
t-RES	14.12	1.19	2.95	1.24	0.00	0.00	7.63	2.51
taxifolin	1.40	1.55	0.54	0.66	0.19	0.94	0.44	1
ferulic_acid	0.28	2.56	1.63	2.05	2.17	0.00	2.13	1.24
rutin	0.82	0.48	0.97	0.47	1.31	0.49	1.09	0.51
PLO	1.07	1.10	0.00	1.76	0.00	1.55	0.49	1.56
ELG	5.32	5.06	2.41	0.64	0.75	2.15	0.94	2.32
AE	10.25	9.25	11.15	9.45	8.15	8.40	3.20	18.31
QUE	5.34	5.08	2.44	0.41	0.27	6.42	0.33	2.35
ABS	1.25	1.18	1.22	1.99	1.80	2.16	2.22	1.38

Epicatechin had values between (3.5 mg/L) in the MM-Mf_MAE variety and 56.14 mg/L in the PN_St_MAE variety. Shikimic acid is an important polyphenolic acid in plant synthesis and was highlighted by large quantities in the grape pomace extract. The highest values were recorded in the extracts obtained from the 'Mamaia' variety (91.57 mg/L) cultivated in the Murfatlar region, (65.08 mg/L) as was recorded in the extracts obtained from the 'Burgund' variety, cultivated in the Stefanesti wine region. Phenolic acids are found in high quantities, for example gallic acid, which is found in the grape pomace extract between 0.05mg/L (BM-St_MAE) and 124.06 mg/L (MM_Mf_MAE). It has a high content for CS_St_MAE (28.30 mg/L) compared to the reference 5,49 mg/100g DW *(Rockenbach, 2011)* for the same variety, but it is low with 'Mamaia' variety, compared to the 'Bordeux' variety in reference *(Rockenbach, 2011).*

Another high phenolic acid is caffeic acid, ranging from 0.03 mg/L (CS_St_MAE) to 38.87 mg/L (MM_Mf_MAE). The syringic acid in pomace is one of the highest value polyphenolic acids. The syringic acid has values between 57.58 mg/L (M_St_MAE) and 597.08 mg/L (CS_Mf_MAE). Resveratrol is the most important polyphenol in the polyphenolic profile of pomace. It is found in the extract of pomace like t-resveratrol (t-RES) and it has values between 0.0 mg/L (BN_Mf_MAE and CS_Mf_MAE) and 7.63 mg/L (MM_Mf_MAE). After the extraction, the wines were fortified with 50 ml/L of MAE extract. Figure 1 and 2 shows the parallel determinations of total polyphenolic compounds with the antioxidant activity of wine varieties before and after fortification with MAE extract. It is observed after fortification the very large increase in the amount of total polyphenol compounds, implicitly of antioxidant activity. The most obvious change (figure 1) is to PNw_St = 1653 mg GAE/L, versus PN_Stw+MAE = 13415 mgGAE/L, it is also seen in the rose wine of PN_St_MAE = 12515 mg GAE/L, but also to wine CS_St w = 5432 mgGAE/L, versus CS_Stw+MAE = 8256 mgGAE/L. In the case of anthocyanins, it is best to observe the fortification of the wine of the variety CS_St = 124.51 mg/L versus CS_Stw+MAE = 378.61 mg/L, t is also seen in the rose wine of PN_St = 48.39 mg/L versus PNr_St _MAE =76.13mg/L. A small growth of anthocyanins is observed in the 'Mamaia' variety, MM_Mf=108.24 mg/L versus MM_Mf_MAE = 151.99 mg/L.

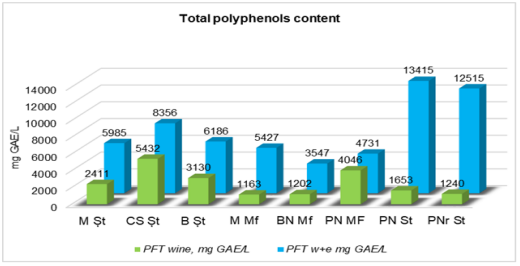


Fig. 1 - Total polyphenol content of wines before and after fortification with extracts obtained by MAE

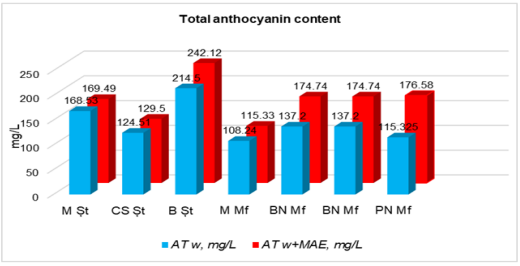


Fig. 2 - Total anthocyanin content of wines before and after fortification with extracts obtained by MAE

The pomace has a high content of catechins, which is observed and figure 3 in which you can see an increase in the concentration of catechins in all wines fortified with MAE extract. The highest content of catechins is observed in wine CS_St_MAE (53.7549 mg/L). In the case of tannin content, it is noted that the highest is the wine MM_Mf_MAE (549.7198 mg/L)

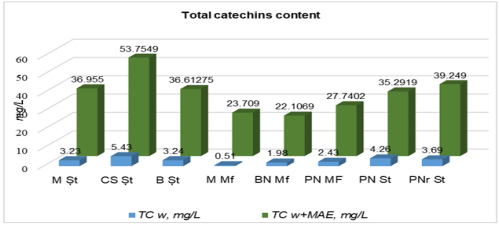


Fig. 3 - Total catechins content of wines before and after fortification with extracts obtained by MAE

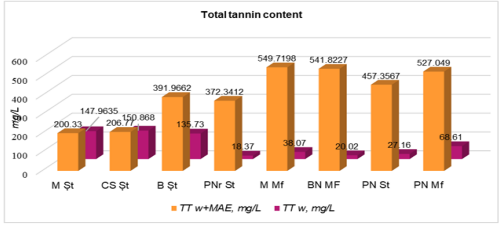


Fig. 4 - Total tannins content of wines before and after fortification with extracts obtained by MAE

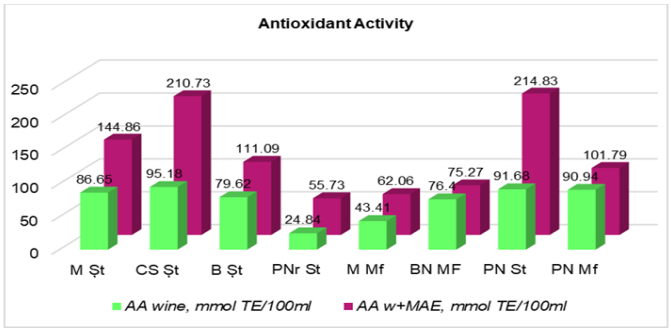


Fig. 5 - The antioxidant activity of wines before and after fortification with extracts obtained by MAE method

As for the antioxidant activity of wines, it grows and takes as much for fortified wines (figure 5). The antioxidant activity at PN_St_MAE is the highest (214.83mmol TE/L), compared to the initial wine PN_Stw= 91.68 mmol TE/L. As a high content of total polyphenols was observed at CS_St, the antioxidant activity being directly proportional to this parameter, CS _ St_MAE (210.73 mmol TE/L) wine has a high antioxidant activity.

The samples were also analysed with HPLC-HRMS to identify individual polyphenolic compounds in wine and fortified wine. Table 3 shows individual polyphenols that were determined from wine before and after fortification with MAE extract.

Table 3

Individual phenolic compounds of of wines before and after fortification with extracts obtained by MAE method

Wine / Individual Polyphenols	B-St	B-St-MAE	CS-St	CS-St-MAE	M-St	M-St-MAE	PN-St	PN-St-MAE	PNr-St	PNr-St-MAE	MM-Mf	MM-Mf-MAE	PN-Mf	PN-Mf-MAE	BN_Mf	BN-Mf-MAE
SHK	31.69	28.05	38.54	39.69	30.41	28.7	20.27	21.31	18.29	21.45	17.67	17.29	27.91	26.63	21.46	23.64
GAL	76.55	69.57	110.7	112.7	67.87	66.84	63.17	62.8	1.93	2.49	14.81	16.57	14.63	16.55	5.78	7.68
3,4-DHBA	6.02	5.01	4.53	4.48	5.85	6.13	4.46	4.61	1.88	1.88	4.31	4.87	5.02	5.2	7.32	7.05
2,5-DHB	1.36	1.16	1.02	1.33	1.01	0.83	0.88	0.89	0.97	0.91	0.72	0.65	1.42	1.58	0.58	0.56
4-HDB	0.89	0.77	0.79	0.8	0.44	0.47	0.68	0.74	0.39	0.38	0.42	0.54	0.92	0.88	0.86	0.91
CFA	8.91	7.97	4.06	3.98	3.7	3.46	1.89	1.67	2.62	2.6	6.39	6.36	13.63	11.7	4.33	4.25
CAT	50.76	49.45	76.05	64.91	30.45	35.64	89.19	78.34	7.24	20.83	15.68	20.58	27.93	37.6	10.10	15.32
ECAT	19.18	17.76	25.56	21.33	12.98	11.59	24.05	24.59	1.21	4.44	3.11	3.85	7.27	10.95	1.24	2.53
SYR	250.1	231.2	406.8	415.5	315.8	283.0	259.3	260.2	10.46	14.07	78.85	81.32	86.61	77.32	33.03	37.78
oenina	8.01	6.22	9.12	6.13	4.64	2.72	4.07	1.95	7.67	4.12	18.64	11.85	38.21	27.01	24.85	17.16
p-CUM	2.29	2.17	1.18	1.37	1.11	1.24	0.99	1.01	0.7	0.74	3.02	3.33	3.75	3.78	4.74	4.87
polidatin	2.06	1.79	0.98	0.85	0.75	0.7	0.96	0.87	0.48	0.41	1.6	1.42	1.23	1.55	0.44	0.56
t-RES	3.03	1.92	1.22	1.05	0.92	1.36	1.63	1.13	0.71	0.39	3.1	3.28	1.95	2.89	1.08	1.15
t-polidatin	442.6	535.7	494.5	474.2	264.8	220.6	710.6	570.5	497.6	391.3	219.7	186.6	625.7	486.1	266.4	209.6
ELG	0.87	0.97	0.92	0.92	0.37	0.59	1.44	1.39	0.09	0.09	0.19	0.55	0.15	0.44	0.23	0.28
AZE	4.54	5.21	4.33	5.08	13.44	4.48	3.88	4.26	7.57	5.33	5.88	4.74	5.21	5.44	6.15	4.76
QEA	0.87	0.97	0.92	0.92	0.37	0.59	1.44	1.39	0.09	0.09	0.19	0.55	0.15	0.44	0.23	0.28

Statistical Data Analysis of *MAE extract, wine and fortified wine*

A distinct interest that conduct to the need to identify and quantify the potential interactions between phytochemical compounds was the large number of results and independent interest variables (figure 6 and 7).

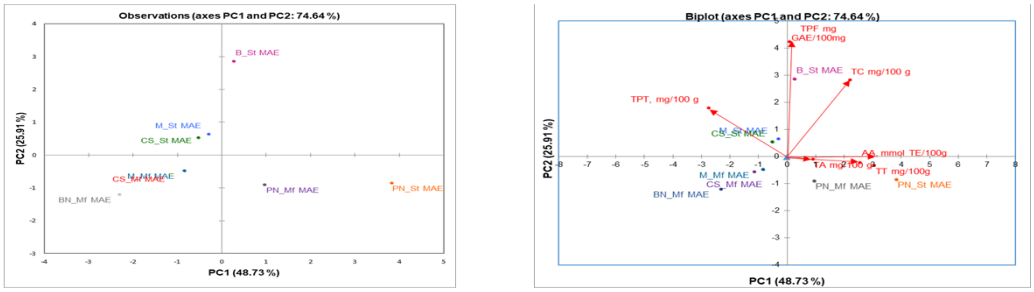
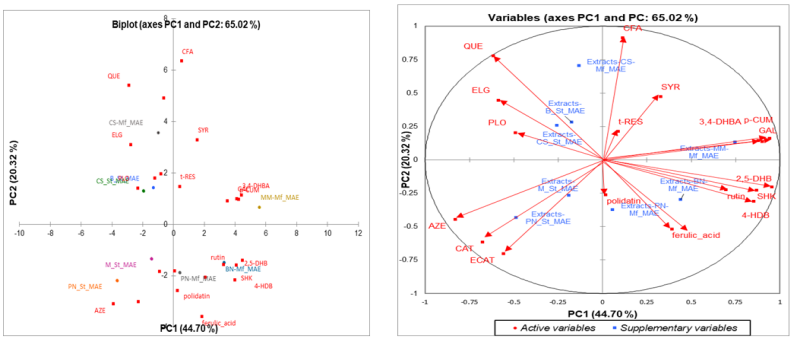


Fig. 6 - Distribution and principal component analyzed (PCA), according to the composition of polyphenolic compounds in the pomace extracts

The influence between the phytochemical elements of grape pomace extracts is shown in Figure 6. The PCA score of 74,64% is a very good score.



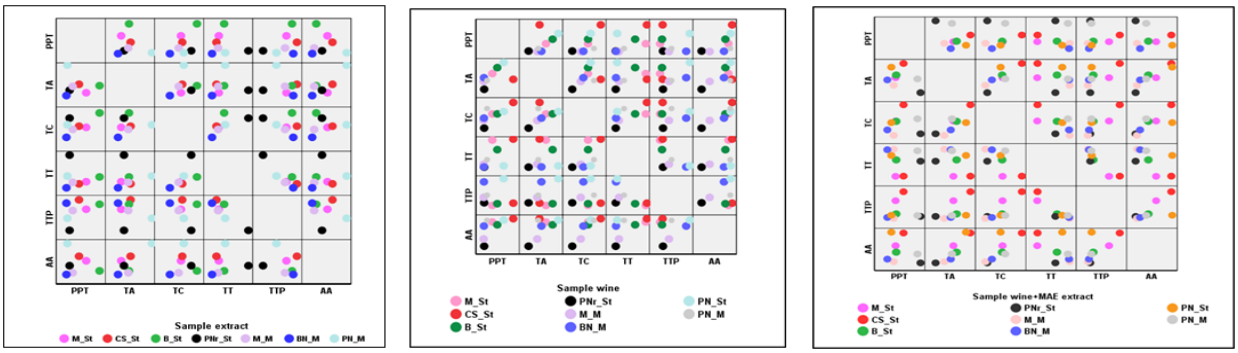
(A) (B)

Fig. 7 - Biplot (A) and distribution (B) of principal component analyzed (PCA), according to the individual polyphenols in pomace extracts

The influence between the individual polyphenols of grape pomace extracts is shown in Figure 7. The PCA score of 65,02% is a very good score.

A distinct interest that conducts to the need to identify and quantify the potential interactions between phytochemical compounds was the large number of results and independent interest variables.

The matrix of the variables of interest in the extract obtained by the microwave assisted extraction method MAE (figure 8,(A)), of the wines before (figure 8(B)) and after fortification with MAE extracts (figure 8(C)) are presented as studied phyto-compound markers (PFT, TA, TC, TT, TTP, AA), respectively, the 8 variants (wine varieties/grape pomace extract).



(A) (B) (C)

Fig. 8 - Correlations between the phytochemical compounds of the pomace extract (A), wine before (B) and after (C) fortification (TPF, TA, TC, TT, TPT and AA), depending on the varieties from which they were produced

Within these statistical analyses correlations are made for each matrix: MAE extracts (Table 4), wine (table 5) and fortified wine (Table 6). In the extracts of grape pomace (Table 4) anthocyanins are distinctly positively correlated with the antioxidant activity (0.804*).

Tannins are very significantly negative correlates with polymerized tannins (-0.889**). Total polyphenols in extracts have a significantly positive correlation with catechins (0.605) and polymerized

tannins (0.418), and with antioxidant activity is negatively correlated (-0.184), with tannins (-0.113), as well as anthocyanins (-0.164).

Table 4

Correlations between the polyphenolic compounds of grape pomace extracts

	Phytochemicals	PPT	TA	TC	TT	TTP	AA
PPT	Pearson Correlation	1	-.164	.605	-.113	.418	-.184
TA	Pearson Correlation	-.164	1	.239	.084	-.216	.804(*)
TC	Pearson Correlation	.605	.239	1	.646	-.342	.119
	Sig. (2-tailed)	.150	.605		.117	.452	.799
TT	Pearson Correlation	-.113	.084	.646	1	-.889(**)	.109
	Sig. (2-tailed)	.809	.857	.117		.007	.816
TTP	Pearson Correlation	.418	-.216	-.342	-.889(**)	1	-.229
	Sig. (2-tailed)	.351	.641	.452	.007		.622
AA	Pearson Correlation	-.184	.804(*)	.119	.109	-.229	1
	Sig. (2-tailed)	.692	.029	.799	.816	.622	

** Correlation is significant at the 0.05 level (2-tailed)*
*** Correlation is significant at the 0.01 level (2-tailed)*

The correlations between polyphenolic compounds in wine depend strongly on the wine variety (Figure 8(B). Figure 6 graphically represents the correlation matrix of the phytochemical compounds of wine. Total polyphenols in wine (Table 5) are distinctly positively correlated with catechins (0.763*), significantly positively correlated with anthocyanins (0.502), tannins (0.606), antioxidant activity (0.631) and significantly negatively correlated with polymerized tannins (-0.059). The antioxidant activity in wine (Table 5) is highly significantly correlated with catechins (0.904**).

Table 5

Correlations between polyphenolic compounds of wine

	Phytochemicals	PPT	TA	TC	TT	TTP	AA
PPT	Pearson Correlation	1	.502	.763(*)	.606	-.059	.631
TA	Pearson Correlation		.205	.028	.111	.889	.093
TC	Pearson Correlation	.502	1	.432	.180	.397	.649
	Sig. (2-tailed)	.205		.286	.670	.330	.081
TT	Pearson Correlation	.763(*)	.432	1	.623	.019	.904(**)
	Sig. (2-tailed)	.028	.286		.099	.965	.002
TTP	Pearson Correlation	.606	.180	.623	1	-.648	.528
	Sig. (2-tailed)	.111	.670	.099		.082	.179
AA	Pearson Correlation	-.059	.397	.019	-.648	1	.226
	Sig. (2-tailed)	.889	.330	.965	.082		.591

** Correlation is significant at the 0.05 level (2-tailed)*
*** Correlation is significant at the 0.01 level (2-tailed)*

Correlations in fortified wines (table 6) are not at all similar to correlations in initial wines (table 5) or correlations in extracts (table 4). Significant positive correlations between PPT and TC (0.112) and TTP (0.111) are observed. Significant negative correlations between PPT and TA (-0.375), TT (-0.332) and AA (-0.229). Also in Table 6 there are observed significant strong positive correlations between TA with TC (0.811) and TTP (0.813).

Table 6

Correlations between polyphenolic compounds of fortified wine

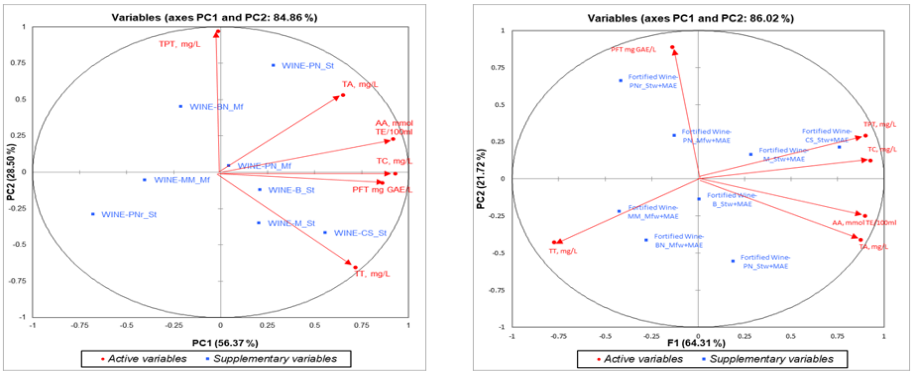
Sample wine+MAE extract		PPT	TA	TC	TT	TTP	AA
PPT	Correlation	1.000	-.375	.112	-.332	.111	-.229
	Significance (2-tailed)	.	.407	.811	.467	.813	.621
TA	Correlation	-.375	1.000	.847	-.577	.750	.923
	Significance (2-tailed)	.407	.	.016	.175	.052	.003
TC	Correlation	.112	.847	1.000	-.753	.898	.776
	Significance (2-tailed)	.811	.016	.	.051	.006	.040
TT	Correlation	-.332	-.577	-.753	1.000	-.837	-.760
	Significance (2-tailed)	.467	.175	.051	.	.019	.047

TTP	Correlation	.111	.750	.898	-.837	1.000	.761
	Significance (2-tailed)	.813	.052	.006	.019	.	.047
AA	Correlation	-.229	.923	.776	-.760	.761	1.000
	Significance (2-tailed)	.621	.003	.040	.047	.047	.

** Correlation is significant at the 0.05 level (2-tailed)*
*** Correlation is significant at the 0.01 level (2-tailed)*

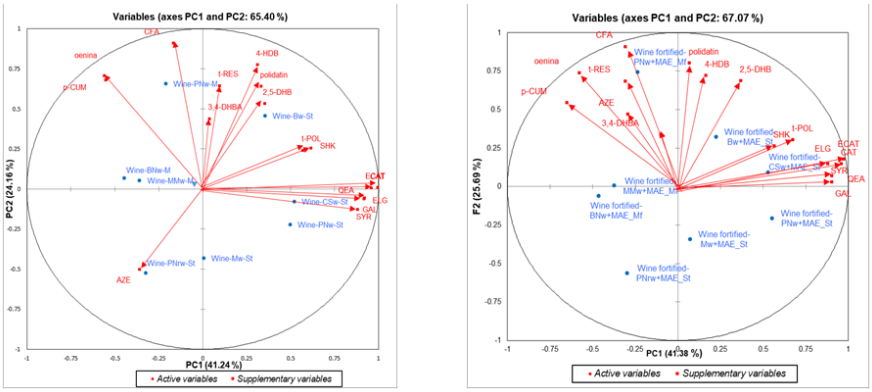
Between the antioxidant activity in fortified wines with the other bio compounds is in a significantly strong positive correlation with TA (0.750), with TC (0.898) and the strong negative correlation with TT (-0.837).

Classification and differentiation between samples of wine (Figure 9 (A)) and fortified wine (figure 9 (B)) based on total phenolic compounds was carried out by multivariate data analysis using Principal Component Analysis (PCA). Figure 9 shows a two-dimensional graph of the eight samples of red wine analysed, defined by the first two main components, PC1 and PC2.



(A) (B)

Fig. 9 - Distribution and principal component analyzed (PCA), according to the composition of total polyphenolic compounds in the wine before (A) and after (B) fortification



(A) (B)

Fig. 10 - Distribution and principal component analyzed (PCA), according to the composition of individual polyphenols in the wine before (A) and after (B) fortification

The multivariate statistical analysis was carried out by separating wines before fortification (Figure 9 (A)) after fortification (Figure 9 (B)), due to the major difference between the phytocomponents introduced from the extract of pomace from fortified wines. PCA has been applied separately to the two wine collections. The first two axes (shown in the diagram) explain 84.86% of the total variation of the phytochemical composition. The maps defined by PC1 and PC2 for PCA on the polyphenolic data on the original wines analysed and are presented in Figure 9 (A) and, in Figure 9 (B), are the polyphenolic data for fortified wines. The PCA score of 84.86% is a very good score. Figure 9 (A) PC1 main component explained by 56.37% of the total variation is opposed to PFT, TT and TC compounds and the remaining measured polyphenols, explained PC2 by 28.5%. The PCA score of 86.02% is a very good score for polyphenolic compounds

determined from fortified wine (figure (B)). Figure 9 (B) PC1 main component explained by 64.31% of the total variation is opposed to AA, TT and TA and the remaining measured polyphenols, explained PC2 by 21.72%.

The PCA score of 65,40% is a very good score. Figure 10 (A) main component PC1 explained by 41.24% of the total variation is opposed to AZE, GAL, SYR, ELG and content phenols at the remaining measured parameters, PC2 explained by 24,16%. The influence of grape pomace extract on the content of individual polyphenols in fortified wines is underlined in Figure 10 (B). The PCA score of 67,07% is a very good score. Figure 10 (B) main component PC1 explained by 41.38% of the total variation and content in the measured parameters remaining in the main component PC2, explained by 25.69%. Table 7 shows Pearson correlations between individual polyphenols of pomace extracts. As observed in table 7, there are some distinctly significant positive correlations between individual polyphenols, such as: between shkimic acid and 3,4- dihidroxibenzoic acid (r^2=0.876**), 2,5- dihidroxibenzoic (r^2=0.949**), 4- hidroxibenzoic (r^2=0.879**). It is also distinctly positively correlated with p- coumaric (r^2=0.786*) and distinctly negative with quercetin (r^2=-0.754*). The gallic acid in the extract of the pomace is distinctly significantly correlated with 3,4-dihidroxibenzoic acid (r^2=0.869**), significantly correlated with 2,5- dihidroxibenzoic (r^2=0.765*), 4-hidroxibenzoic (r^2=0.737*), p-coumarir acid (r^2=0.709*) and azelaic acid (r^2=0.717*), and significantly negatively correlated with ellagic acid (r^2=-0.712*).

Table 8 correlates individual polyphenols in wine. As expected in red wine, gallic acid is highly correlated with epicatechin (r^2=0.931**) and syringic acid(r^2=0.981**), and with shkimic (r^2=0.803*), catechin (r^2=0.814**), ellagic acid (r^2=0.739**) and quercetin (r^2=0.739**), is significantly positively correlated. The individual compound polydatin (r^2= 0.939**) in wine, being a precursor to resveratrol, is distinctly significantly correlated with t-resveratrol in wine. The individual compound polydatin in wine, being a precursor to resveratrol, is distinctly significantly correlated with t-resveratrol in wine (r^2=0.939**). For fortified wines, the correlation of individual polyphenolic compounds is shown in Table 9. In fortified wines, very significant correlations between individual polyphenolic compounds are preserved. A clear example is epicatechin which correlates very distinctly significantly with catechin (r2=0.834**), gallic acid (r2=0.831**), ellagic acid (r2=0.912**) and quercetin (r2=0.912**). T-polydatin stilbene forms t-resveratrol. The individual compound t-polydatin in fortified wine correlates significantly with catechin and epicatechin. Due to the fortification with polyphenolic compounds from the extracts of pomace, fortified wine has different correlations between the individual polyphenolic components. There may be negative correlations between the stilbene that are normally distinctly positively correlated, as t-polydatin (r^2=-0.202) is related t-resveratrol, although it is its precursor.

Table 7

Correlations between the individual polyphenols of grape pomace extracts

Individual polyphenols		SHK	GAL	3,4-DHBA	2,5-DHB	4-HDB	CAT	CFA	ECAT	SYR	p-CUM	Polydatin	t-RES	taxifolin	ferulic_acid	rutin	PLO	ELG	AE	QUE	ABS
SHK	Pearson Correlation	1	.694	.876(**)	.949(**)	.879(**)	-.375	.023	-.190	.160	.786(*)	.198	.171	-.627	.372	.440	-.158	-.672	-.614	-.754(*)	.706
	Sig. (2-tailed)		.056	.004	.000	.004	.360	.956	.652	.705	.021	.638	.686	.096	.364	.275	.708	.068	.105	.031	.050
GAL	Pearson Correlation	.694	1	.869(**)	.765(*)	.737(*)	-.653	.132	-.522	.600	.709(*)	.050	.057	-.626	.059	.668	-.374	-.536	-.712(*)	-.401	.717(*)
	Sig. (2-tailed)	.056		.005	.027	.037	.079	.756	.184	.116	.049	.907	.893	.097	.890	.070	.361	.171	.048	.325	.045
3,4-DHBA	Pearson Correlation	.876(**)	.869(**)	1	.910(**)	.752(*)	-.671	.313	-.518	.439	.919(**)	-.107	.156	-.583	.164	.531	-.256	-.582	-.788(*)	-.482	.820(*)
	Sig. (2-tailed)	.004	.005		.002	.031	.069	.450	.189	.276	.001	.801	.711	.129	.699	.175	.540	.130	.020	.226	.013
2,5-DHB	Pearson Correlation	.949(**)	.765(*)	.910(**)	1	.910(**)	-.487	.010	-.332	.138	.891(**)	.054	.136	-.671	.487	.631	-.395	-.626	-.683	-.760(*)	.629
	Sig. (2-tailed)	.000	.027	.002		.002	.221	.980	.421	.744	.003	.898	.748	.069	.221	.093	.333	.097	.062	.029	.095
4-HDB	Pearson Correlation	.879(**)	.737(*)	.752(*)	.910(**)	1	-.341	-.107	-.211	-.002	.709(*)	.355	.279	-.542	.484	.645	-.373	-.450	-.573	-.741(*)	.413
	Sig. (2-tailed)	.004	.037	.031	.002		.408	.802	.615	.996	.049	.388	.504	.165	.224	.084	.362	.263	.138	.035	.309
CAT	Pearson Correlation	-.375	-.653	-.671	-.487	-.341	1	-.581	.933(**)	-.618	-.603	.018	.120	.158	-.190	-.253	.207	.145	.900(**)	-.060	-.590
	Sig. (2-tailed)	.360	.079	.069	.221	.408		.131	.001	.102	.113	.966	.776	.708	.652	.545	.623	.732	.002	.888	.124
CFA	Pearson Correlation	.023	.132	.313	.010	-.107	-.581	1	-.621	.270	.332	-.232	.420	.508	-.395	-.256	.310	.422	-.492	.609	.266
	Sig. (2-tailed)	.956	.756	.450	.980	.802	.131		.100	.518	.422	.580	.300	.199	.333	.540	.455	.297	.216	.109	.524
ECAT	Pearson Correlation	-.190	-.522	-.518	-.332	-.211	.933(**)	-.621	1	-.456	-.544	.100	-.049	.049	-.086	-.326	.370	-.085	.883(**)	-.230	-.352
	Sig. (2-tailed)	.652	.184	.189	.421	.615	.001	.100		.256	.163	.814	.908	.908	.840	.430	.367	.842	.004	.584	.392
SYR	Pearson Correlation	.160	.600	.439	.138	-.002	-.618	.270	-.456	1	.138	-.024	-.460	-.311	-.294	-.015	.159	-.447	-.422	.131	.764(*)
	Sig. (2-tailed)	.705	.116	.276	.744	.996	.102	.518	.256		.744	.955	.252	.453	.479	.971	.707	.267	.297	.758	.027
p-CUM	Pearson Correlation	.786(*)	.709(*)	.919(**)	.891(**)	.709(*)	-.603	.332	-.544	.138	1	-.302	.307	-.497	.267	.636	-.457	-.397	-.758(*)	-.457	.574
	Sig. (2-tailed)	.021	.049	.001	.003	.049	.113	.422	.163	.744		.467	.460	.211	.522	.090	.254	.331	.029	.254	.137
Polydatin	Pearson Correlation	.198	.050	-.107	.054	.355	.018	-.232	.100	-.024	-.302	1	-.035	.075	.298	-.175	.250	-.001	-.090	-.206	-.036
	Sig. (2-tailed)	.638	.907	.801	.898	.388	.966	.580	.814	.955	.467		.935	.860	.474	.679	.551	.999	.831	.625	.933
t-RES	Pearson Correlation	.171	.057	.156	.136	.279	.120	.420	-.049	-.460	.307	-.035	1	.311	-.345	.218	-.069	.471	-.132	.162	-.225
	Sig. (2-tailed)	.686	.893	.711	.748	.504	.776	.300	.908	.252	.460	.935		.454	.402	.604	.871	.239	.755	.702	.592
taxifolin	Pearson Correlation	-.627	-.626	-.583	-.671	-.542	.158	.508	.049	-.311	-.497	.075	.311	1	-.308	-.675	.549	.900(**)	.322	.792(*)	-.554
	Sig. (2-tailed)	.096	.097	.129	.069	.165	.708	.199	.908	.453	.211	.860	.454		.459	.066	.158	.002	.437	.019	.154
ferulic_acid	Pearson Correlation	.372	.059	.164	.487	.484	-.190	-.395	-.086	-.294	.267	.298	-.345	-.308	1	.253	-.360	-.279	-.238	-.653	-.040
	Sig. (2-tailed)	.364	.890	.699	.221	.224	.652	.333	.840	.479	.522	.474	.402	.459		.545	.381	.504	.570	.079	.926

rutin	Pearson Correlation	.440	.668	.531	.631	.645	-.253	-.256	-.326	-.015	.636	-.175	.218	-.675	.253	1	-.903(**)	-.322	-.442	-.514	.117
	Sig. (2-tailed)	.275	.070	.175	.093	.084	.545	.540	.430	.971	.090	.679	.604	.066	.545		.002	.436	.273	.193	.782
PLO	Pearson Correlation	-.158	-.374	-.256	-.395	-.373	.207	.310	.370	.159	-.457	.250	-.069	.549	-.360	-.903(**)	1	.151	.357	.368	.140
	Sig. (2-tailed)	.708	.361	.540	.333	.362	.623	.455	.367	.707	.254	.551	.871	.158	.381	.002		.722	.385	.370	.742
ELG	Pearson Correlation	-.672	-.536	-.582	-.626	-.450	.145	.422	-.085	-.447	-.397	-.001	.471	.900(**)	-.279	-.322	.151	1	.232	.769(*)	-.742(*)
	Sig. (2-tailed)	.068	.171	.130	.097	.263	.732	.297	.842	.267	.331	.999	.239	.002	.504	.436	.722		.580	.026	.035
AE	Pearson Correlation	-.614	-.712(*)	-.788(*)	-.683	-.573	.900(**)	-.492	.883(**)	-.422	-.758(*)	-.090	-.132	.322	-.238	-.442	.357	.232	1	.162	-.590
	Sig. (2-tailed)	.105	.048	.020	.062	.138	.002	.216	.004	.297	.029	.831	.755	.437	.570	.273	.385	.580		.702	.123
QUE	Pearson Correlation	-.754(*)	-.401	-.482	-.760(*)	-.741(*)	-.060	.609	-.230	.131	-.457	-.206	.162	.792(*)	-.653	-.514	.368	.769(*)	.162	1	-.334
	Sig. (2-tailed)	.031	.325	.226	.029	.035	.888	.109	.584	.758	.254	.625	.702	.019	.079	.193	.370	.026	.702		.419
ABS	Pearson Correlation	.706	.717(*)	.820(*)	.629	.413	-.590	.266	-.352	.764(*)	.574	-.036	-.225	-.554	-.040	.117	.140	-.742(*)	-.590	-.334	1
	Sig. (2-tailed)	.050	.045	.013	.095	.309	.124	.524	.392	.027	.137	.933	.592	.154	.926	.782	.742	.035	.123	.419	

** *Correlation is significant at the 0.01 level (2-tailed).*

* *Correlation is significant at the 0.05 level (2-tailed).*

Table 8

Correlations between the individual polyphenols of wine

Individual polyphenols		SHK	GAL	3,4-DHBA	2,5-DHB	4-HDB	CFA	CAT	ECAT	SYR	oenina	p-CUM	polydatin	t-RES	t-polydatin	ELG	AZE	QEA
SHK	Pearson Correlation	1	.803(*)	.309	.550	.469	.244	.467	.646	.782(*)	-.114	-.179	.240	-.046	.153	.303	.019	.303
	Sig. (2-tailed)		.016	.456	.158	.242	.560	.243	.084	.022	.789	.672	.566	.915	.718	.465	.965	.465
GAL	Pearson Correlation	.803(*)	1	.165	.298	.225	-.179	.814(*)	.931(**)	.981(**)	-.569	-.519	.289	.032	.251	.739(*)	-.078	.739(*)
	Sig. (2-tailed)	.016		.697	.473	.592	.672	.014	.001	.000	.141	.188	.488	.940	.548	.036	.854	.036
3,4-DHBA	Pearson Correlation	.309	.165	1	-.078	.581	.242	.023	.088	.179	.269	.623	.137	.160	-.316	.081	.073	.081
	Sig. (2-tailed)	.456	.697		.854	.131	.564	.958	.836	.671	.520	.099	.745	.706	.445	.849	.864	.849
2,5-DHB	Pearson Correlation	.550	.298	-.078	1	.402	.686	.224	.333	.263	.139	-.152	.507	.254	.582	.096	-.101	.096
	Sig. (2-tailed)	.158	.473	.854		.324	.061	.594	.420	.529	.742	.720	.199	.543	.130	.821	.813	.821
4-HDB	Pearson Correlation	.469	.225	.581	.402	1	.544	.330	.322	.146	.468	.521	.266	.196	.428	.291	-.584	.291
	Sig. (2-tailed)	.242	.592	.131	.324		.163	.425	.437	.731	.242	.186	.524	.643	.291	.485	.129	.485
CFA	Pearson Correlation	.244	-.179	.242	.686	.544	1	-.195	-.155	-.202	.748(*)	.561	.575	.544	.185	-.314	-.239	-.314
	Sig. (2-tailed)	.560	.672	.564	.061	.163		.643	.714	.631	.033	.148	.136	.163	.660	.449	.569	.449
CAT	Pearson Correlation	.467	.814(*)	.023	.224	.330	-.195	1	.964(**)	.795(*)	-.448	-.469	.237	.075	.628	.956(**)	-.436	.956(**)
	Sig. (2-tailed)	.243	.014	.958	.594	.425	.643		.000	.018	.266	.241	.572	.859	.096	.000	.280	.000
ECAT	Pearson Correlation	.646	.931(**)	.088	.333	.322	-.155	.964(**)	1	.908(**)	-.520	-.519	.304	.079	.533	.908(**)	-.296	.908(**)
	Sig. (2-tailed)	.084	.001	.836	.420	.437	.714	.000		.002	.187	.188	.465	.853	.174	.002	.477	.002
SYR	Pearson Correlation	.782(*)	.981(**)	.179	.263	.146	-.202	.795(*)	.908(**)	1	-.555	-.535	.212	-.035	.201	.702	.050	.702
	Sig. (2-tailed)	.022	.000	.671	.529	.731	.631	.018	.002		.154	.172	.614	.935	.634	.052	.906	.052
oenina	Pearson Correlation	-.114	-.569	.269	.139	.468	.748(*)	-.448	-.520	-.555	1	.840(**)	.040	.186	-.046	-.554	-.234	-.554
	Sig. (2-tailed)	.789	.141	.520	.742	.242	.033	.266	.187	.154		.009	.926	.660	.914	.154	.576	.154
p-CUM	Pearson Correlation	-.179	-.519	.623	-.152	.521	.561	-.469	-.519	-.535	.840(**)	1	.109	.310	-.320	-.446	-.228	-.446
	Sig. (2-tailed)	.672	.188	.099	.720	.186	.148	.241	.188	.172	.009		.797	.455	.440	.268	.587	.268
polydatin	Pearson Correlation	.240	.289	.137	.507	.266	.575	.237	.304	.212	.040	.109	1	.939(**)	.149	.243	-.386	.243
	Sig. (2-tailed)	.566	.488	.745	.199	.524	.136	.572	.465	.614	.926	.797		.001	.725	.562	.345	.562
t-RES	Pearson Correlation	-.046	.032	.160	.254	.196	.544	.075	.079	-.035	.186	.310	.939(**)	1	.006	.119	-.441	.119
	Sig. (2-tailed)	.915	.940	.706	.543	.643	.163	.859	.853	.935	.660	.455	.001		.989	.779	.274	.779
t-polydatin	Pearson Correlation	.153	.251	-.316	.582	.428	.185	.628	.533	.201	-.046	-.320	.149	.006	1	.578	-.560	.578
	Sig. (2-tailed)	.718	.548	.445	.130	.291	.660	.096	.174	.634	.914	.440	.725	.989		.133	.149	.133
ELG	Pearson Correlation	.303	.739(*)	.081	.096	.291	-.314	.956(**)	.908(**)	.702	-.554	-.446	.243	.119	.578	1	-.443	1.000(**)
	Sig. (2-tailed)	.465	.036	.849	.821	.485	.449	.000	.002	.052	.154	.268	.562	.779	.133		.272	.000
AZE	Pearson Correlation	.019	-.078	.073	-.101	-.584	-.239	-.436	-.296	.050	-.234	-.228	-.386	-.441	-.560	-.443	1	-.443
	Sig. (2-tailed)	.965	.854	.864	.813	.129	.569	.280	.477	.906	.576	.587	.345	.274	.149	.272		.272
QEA	Pearson Correlation	.303	.739(*)	.081	.096	.291	-.314	.956(**)	.908(**)	.702	-.554	-.446	.243	.119	.578	1.000(**)	-.443	1
	Sig. (2-tailed)	.465	.036	.849	.821	.485	.449	.000	.002	.052	.154	.268	.562	.779	.133	.000	.272	

** *Correlation is significant at the 0.01 level (2-tailed).*

* *Correlation is significant at the 0.05 level (2-tailed).*

Table 9

Correlations between the individual polyphenols of fortified wine

Individual polyphenols		SHK	GAL	3,4-DHBA	2,5-DHB	4-HDB	CFA	CAT	ECAT	SYR	genina	p-CUM	polydatin	t-RES	t-polydatin	ELG	AZE	QEA
SHK	Pearson Correlation	1	.783(*)	.117	.593	.336	.057	.450	.518	.752(*)	-.094	-.234	-.008	-.267	.312	.245	.255	.245
	Sig. (2-tailed)		.021	.784	.121	.416	.893	.263	.189	.031	.825	.577	.984	.523	.452	.559	.543	.559
GAL	Pearson Correlation	.783(*)	1	.089	.361	.172	-.207	.785(*)	.834(**)	.991(**)	-.509	-.514	.104	-.217	.399	.732(*)	-.213	.732(*)
	Sig. (2-tailed)	.021		.835	.380	.684	.623	.021	.010	.000	.197	.193	.806	.605	.328	.039	.613	.039
3,4-DHBA	Pearson Correlation	.117	.089	1	-.218	.557	.216	-.090	-.057	.119	.362	.639	.153	.303	-.420	.107	-.411	.107
	Sig. (2-tailed)	.784	.835		.604	.152	.608	.832	.892	.779	.378	.088	.717	.465	.300	.801	.312	.801
2,5-DHB	Pearson Correlation	.593	.361	-.218	1	.366	.596	.445	.482	.323	.325	-.136	.463	.182	.701	.193	.634	.193
	Sig. (2-tailed)	.121	.380	.604		.373	.119	.269	.226	.435	.432	.748	.248	.667	.053	.647	.091	.647
4-HDB	Pearson Correlation	.336	.172	.557	.366	1	.430	.300	.301	.135	.570	.591	.337	.194	.334	.299	.117	.299
	Sig. (2-tailed)	.416	.684	.152	.373		.288	.470	.468	.750	.140	.123	.414	.645	.419	.472	.783	.472
CFA	Pearson Correlation	.057	-.207	.216	.596	.430	1	-.187	-.139	-.249	.785(*)	.563	.807(*)	.770(*)	.078	-.168	.616	-.168
	Sig. (2-tailed)	.893	.623	.608	.119	.288		.658	.743	.551	.021	.146	.015	.025	.855	.691	.104	.691
CAT	Pearson Correlation	.450	.785(*)	-.090	.445	.300	-.187	1	.989(**)	.791(*)	-.402	-.530	.160	-.187	.794(*)	.917(**)	-.276	.917(**)
	Sig. (2-tailed)	.263	.021	.832	.269	.470	.658		.000	.019	.324	.176	.705	.657	.019	.001	.508	.001
ECAT	Pearson Correlation	.518	.834(**)	-.057	.482	.301	-.139	.989(**)	1	.831(*)	-.417	-.538	.211	-.186	.775(*)	.912(**)	-.228	.912(**)
	Sig. (2-tailed)	.189	.010	.892	.226	.468	.743	.000		.011	.304	.169	.615	.659	.024	.002	.587	.002
SYR	Pearson Correlation	.752(*)	.991(**)	.119	.323	.135	-.249	.791(*)	.831(*)	1	-.518	-.528	.054	-.210	.370	.740(*)	-.302	.740(*)
	Sig. (2-tailed)	.031	.000	.779	.435	.750	.551	.019	.011		.189	.178	.899	.618	.367	.036	.467	.036
genina	Pearson Correlation	-.094	-.509	.362	.325	.570	.785(*)	-.402	-.417	-.518	1	.840(**)	.372	.594	-.093	-.428	.461	-.428
	Sig. (2-tailed)	.825	.197	.378	.432	.140	.021	.324	.304	.189		.009	.365	.121	.826	.290	.250	.290
p-CUM	Pearson Correlation	-.234	-.514	.639	-.136	.591	.563	-.530	-.538	-.528	.840(**)	1	.293	.546	-.430	-.378	.150	-.378
	Sig. (2-tailed)	.577	.193	.088	.748	.123	.146	.176	.169	.178	.009		.482	.161	.288	.356	.723	.356
polydatin	Pearson Correlation	-.008	.104	.153	.463	.337	.807(*)	.160	.211	.054	.372	.293	1	.802(*)	.202	.318	.313	.318
	Sig. (2-tailed)	.984	.806	.717	.248	.414	.015	.705	.615	.899	.365	.482		.017	.631	.443	.450	.443
t-RES	Pearson Correlation	-.267	-.217	.303	.182	.194	.770(*)	-.187	-.186	-.210	.594	.546	.802(*)	1	-.202	.008	.127	.008
	Sig. (2-tailed)	.523	.605	.465	.667	.645	.025	.657	.659	.618	.121	.161	.017		.632	.984	.765	.984
t-polydatin	Pearson Correlation	.312	.399	-.420	.701	.334	.078	.794(*)	.775(*)	.370	-.093	-.430	.202	-.202	1	.578	.229	.578
	Sig. (2-tailed)	.452	.328	.300	.053	.419	.855	.019	.024	.367	.826	.288	.631	.632		.133	.586	.133
ELG	Pearson Correlation	.245	.732(*)	.107	.193	.299	-.168	.917(**)	.912(**)	.740(*)	-.428	-.378	.318	.008	.578	1	-.476	1.000(**)
	Sig. (2-tailed)	.559	.039	.801	.647	.472	.691	.001	.002	.036	.290	.356	.443	.984	.133		.233	.000
AZE	Pearson Correlation	.255	-.213	-.411	.634	.117	.616	-.276	-.228	-.302	.461	.150	.313	.127	.229	-.476	1	-.476
	Sig. (2-tailed)	.543	.613	.312	.091	.783	.104	.508	.587	.467	.250	.723	.450	.765	.586	.233		.233
QEA	Pearson Correlation	.245	.732(*)	.107	.193	.299	-.168	.917(**)	.912(**)	.740(*)	-.428	-.378	.318	.008	.578	1.000(**)	-.476	1
	Sig. (2-tailed)	.559	.039	.801	.647	.472	.691	.001	.002	.036	.290	.356	.443	.984	.133	.000	.233	

*** Correlation is significant at the 0.01 level (2-tailed).*

** Correlation is significant at the 0.05 level (2-tailed).*

CONCLUSIONS

In order to realize the negative impact of waste from the wine industry on the environment, in order to have a sustainable agriculture, this industry must move from a linear economy to a circular one. For this purpose, it is assumed to valorised the wine by-products from the wine industry.

The wine by-products are considered natural waste, with great potential for processing and its use in fortifying food. Food obtained by fortification with the by-products of winemaking is a predominant source of bioactive compounds such as: flavonoids, anthocyanins, procyanidins, tannins, catechins, resveratrol, etc.

The pomace extracts resulting from advanced MAE techniques give positive results on optimal extraction conditions, including extraction cost, recovery rate and percentage of purity, stability and toxicity to the environment.

As regards the MAE method, the prediction interval at a 95% confidence level for antioxidant activity ranged from 90.04 mMol TE/100 mg (BN_Mf) to 244.62 mMol TE/100 g pomace (CS_St), and for the total polyphenol content, it ranged from 1523.7 mg GAE/100g (also at BN_Mf) to 2198.7 mg GAE/100 g (B_St) pomace the obtained values were higher than those obtained in bibliography by other advanced extraction methods [25].

The TPC of the extracts showed that the Burgund pomace from Stefanesti and AT from the Pinot Noir pomace variety from Murfatlar, have great potential as a source of antioxidant compounds for food applications. In addition, the content of bioactive compounds increased using the MAE extraction method and proved to be effective for the extraction of phenolic compounds from winemaking waste. However, by fortifying wines with extracts obtained by MAE method, very high values were obtained both TPC (CS_Stw+MAE = 8356 mgGAE/L and PN_St_w+MAE = 13415 mg GAE/L), TA (CS_Stw+MAE = 378.61 mg/L and PN_Stw+MAE = 218.05mg/L) and their antioxidant activity were high (PN_Stw+MAE =214.83 mMol TE/L). Although there are high values of biocompounds in fortified wines, the correlations between these bioactive compounds in fortified wine are only positively or negatively correlated at a significant level.

Due to the fortification with polyphenolic compounds from the extracts of pomace, fortified wine has different correlations between the individual polyphenolic components. There may be negative correlations

between the stilbene that are normally distinctly positively correlated, as t-polydatin (r2=-0.202) is related t-resveratrol, although it is its precursor.

Future research may evaluate the use of other methods of clean extractives, organic solvents and dispersion materials to obtain bioactive compounds (tannins, anthocyanins, etc.) for food fortification.

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IMPLEMENTATION OF A MICROHYDROPOWER SYSTEM FOR SUSTAINABLE AERATION OF FISH PONDS

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REALIZAREA UNUI SISTEM MICROHIDROENERGETIC PENTRU AERAREA SUSTENABILĂ A BAZINELOR PISCICOLE

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Keywords: micro-hydro energy, fishpond aeration, renewable energy, aquatic ecosystems, sustainability

ABSTRACT

The paper presents the manufacturing technology developed at INMA Bucharest for the experimental model Micro-Hydro Energy System SME 1,5-0, designed for converting hydraulic energy into electrical power used to drive aeration systems in aquaculture basins. By integrating renewable energy sources with aeration technologies, the proposed solution contributes to enhancing water quality, reducing phosphorus loads and algal blooms, eliminating pathogenic bacteria, and mitigating discomfort caused by mosquitoes and odors. Controlled aeration optimizes the aquatic habitat, supporting increased fish productivity and ecosystem stability. The sheet-metal components were manufactured using CNC technologies (cutting, punching, bending, and laser cutting), ensuring high precision and improved reliability of the assembly. The results demonstrate that the system can serve as a viable and sustainable alternative for the efficient utilization of zootechnical and aquaculture resources, with a positive impact on the environment and the circular economy.

REZUMAT

Lucrarea prezintă tehnologia de realizare în cadrul INMA București a modelului experimental Sistem Microhidroenergetic SME 1,5-0, destinat conversiei energiei hidraulice în energie electrică utilizată pentru acționarea sistemelor de aerare în bazinele piscicole. Prin integrarea energiei regenerabile cu tehnologiile de aerare, soluția propusă contribuie la îmbunătățirea calității apei, la reducerea încărcărilor de fosfor și a înfloririlor algale, la eliminarea bacteriilor patogene și la diminuarea disconfortului generat de țânțari și mirosuri. Aerarea controlată optimizează habitatul acvatic, susținând creșterea productivității piscicole și stabilitatea ecosistemului. Execuția componentelor din tablă a fost realizată prin tehnologii CNC (debitare, stanțare, îndoire și tăiere cu laser), ceea ce a permis obținerea unei precizii ridicate și a unei fiabilități sporite a ansamblului. Rezultatele obținute demonstrează că sistemul poate constitui o alternativă viabilă și sustenabilă pentru valorificarea eficientă a resurselor zootehnice și piscicole, cu impact pozitiv asupra mediului și economiei circulare.

INTRODUCTION

The growing global demand for sustainable and decentralized energy solutions has intensified interest in micro-hydropower systems (MHES), which are considered viable options for rural and semi-urban applications. These systems harness the kinetic and potential energy of water currents to generate electricity with minimal environmental impact, representing a valuable component of the local renewable energy mix. (*Boroomandnia et al., 2022; Pokharel et al., 2008*).

In recent years, the increasing impact of climate change on water resources and their quality has become increasingly evident. Among the main indicators of the ecological status of aquatic ecosystems, dissolved oxygen represents a key parameter for maintaining biological balance and water quality. (*Boyd, 1998*). Ensuring optimal oxygen concentrations is achieved mainly through natural or artificial aeration processes, which represent the fundamental method for improving water quality and supporting aquatic life. (*Kahil & Seif, 2014; Roy et al., 2021*).

Recent studies highlight the potential of micro-hydropower installations not only for electricity generation, but also for their integration with other energy-dependent systems, such as aeration technologies used in aquaculture and wastewater treatment. (*Emamipour et al., 2025; Munaaim et al., 2021*).

Micro-hydropower systems represent an efficient and sustainable solution for aquaculture, harnessing the kinetic energy of water to generate on-site electricity. Supplying aeration systems with renewable energy reduces dependence on the electrical grid and optimizes the energy consumption of fish farms. At the same time, these systems help maintain optimal dissolved oxygen levels, supporting fish health and the productivity of fish ponds, while promoting efficient energy and environmental management of aquatic ecosystems. *(Nugraha et al., 2025).*

Technological advances in computer numerical control (CNC) machining and numerical simulations (CFD – Computational Fluid Dynamics) have enabled the design and optimization of high-efficiency micro-hydropower components, including penstocks, turbines and control assemblies. (*Putra et al., 2022*). Sustainability assessments also show that community-scale micro-hydropower systems can contribute to strengthening local economies and promoting the circular use of resources. (*Chhetri et al., 2009*).

In this context, the present paper introduces the fabrication of the experimental model Micro-Hydropower System SME 1.5-0, designed and developed at INMA Bucharest. The system is intended for converting hydraulic energy into electrical energy used to power aeration systems in fish ponds, representing an innovative integration of renewable energy and environmental management technologies.

MATERIALS AND METHODS

Precision in sheet metal component manufacturing is an essential factor that influences the reliability and performance of the experimental system Micro-Hydro Energy System SME 1.5-0. To ensure high dimensional accuracy, increased repeatability, and superior structural integrity, advanced CNC (Computer Numerical Control) technologies were employed.

Two types of sheet metal, S235JR and S275JR, were used for the fabrication of experimental system components, selected according to the mechanical demands of the parts.

- The S235JR sheet metal components were processed according to the following workflow:
  - cutting on the HST-C 6/2500 CNC center (fig. 1);
  - punching on the ALPHA-CADMAN 1012T CNC center (fig. 2);
  - bending on the PPEB-4 C CNC center (fig. 3).
- The S275JR sheet metal components were processed by:
  - CNC laser cutting on the Laser FC 1530-S system (fig. 4);
  - bending on the PPEB-4 C CNC center (fig. 3).

All parts were subsequently subjected to CNC inspection for dimensional and tolerance control.

The validated parts were directed to the assembly stage for integration into the experimental system assembly.

This differentiated approach allowed for the optimization of the manufacturing process, adaptation to the mechanical properties of the materials, and ensured the precision, repeatability, and structural integrity of all components.

Sheet metal cutting was carried out using the HST-C 6/2500 CNC cutting center (fig. 1), which allows processing sheets up to [6 mm] thick with a positioning accuracy of ±0.1 mm. The equipment ensures precise contouring of the parts and minimizes thermal deformation.

Fig. 1 - HST-C 6/2500 cutting center, highlighting the cutting head and the working area

The components were punched on the ALPHA-CADMAN 1012T punching center (fig. 2), which provides high repeatability and enables the creation of complex patterns using various dies. The main parameters include a maximum punching force of [300 kN], a table size of [2000 × 1000 mm], and an operating speed of [15 strokes/min].

Fig. 2 - CNC punching center with key components highlighted

Component bending was performed using the PPEB-4 C bending center (fig. 3), which allows bending sheets up to [4 mm] thick and angles up to [90°]. The system minimizes unwanted deformations and ensures uniformity of the components.

Fig. 3 - CNC bending center in operation, showing the active die and the workpiece

Final cutting and the creation of complex profiles were performed using the Laser FC 1530-S CNC system (Fig. 4), capable of processing sheets up to [12 mm] thick with tolerances of ±0.05 mm. This process ensures clean edges and precise contours of the components.

Fig. 4 - Laser cutting system in operation, highlighting the laser beam and the workpiece

The application of CNC technologies and the use of S235JR and S275JR materials enabled the production of components with precise shapes, high repeatability, and appropriate structural integrity.

After completing the machining processes, the components were dimensionally inspected on a control bench equipped with certified metrological instruments, calibrated in specialized laboratories.

The inspection aimed to confirm compliance with the tolerances and dimensions specified in the design.

Parts that met the compliance criteria were forwarded to the assembly stage of the experimental system.

RESULTS AND DISCUSSION

A sheet metal part with a thickness of 4 mm was produced, featuring a 90° bend and a circular hole on one face. The complete CAD model was created in SolidWorks, shown in Figure 5, and the generated DXF file is presented in figure 6.

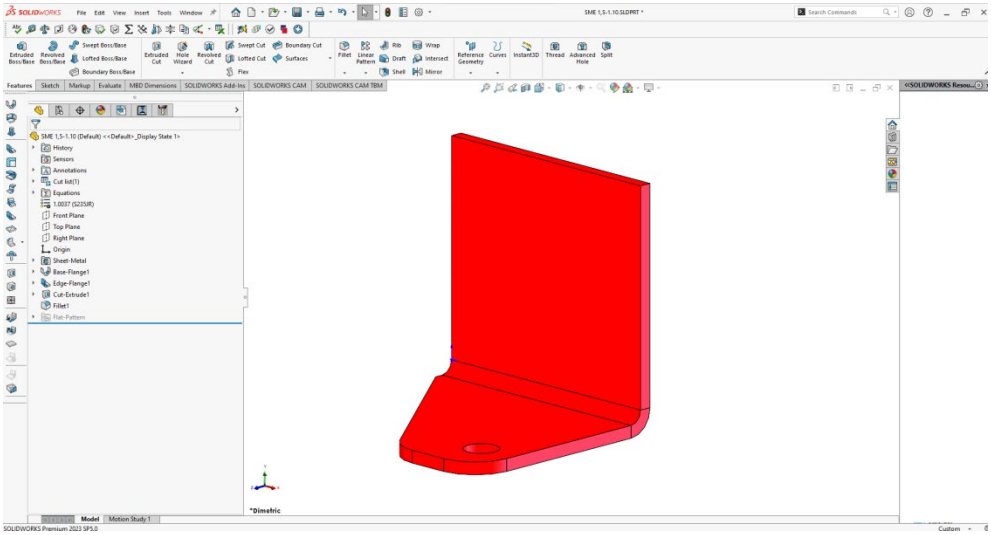

Fig. 5 - CAD model of the machined part, showing the outer contour and the hole position

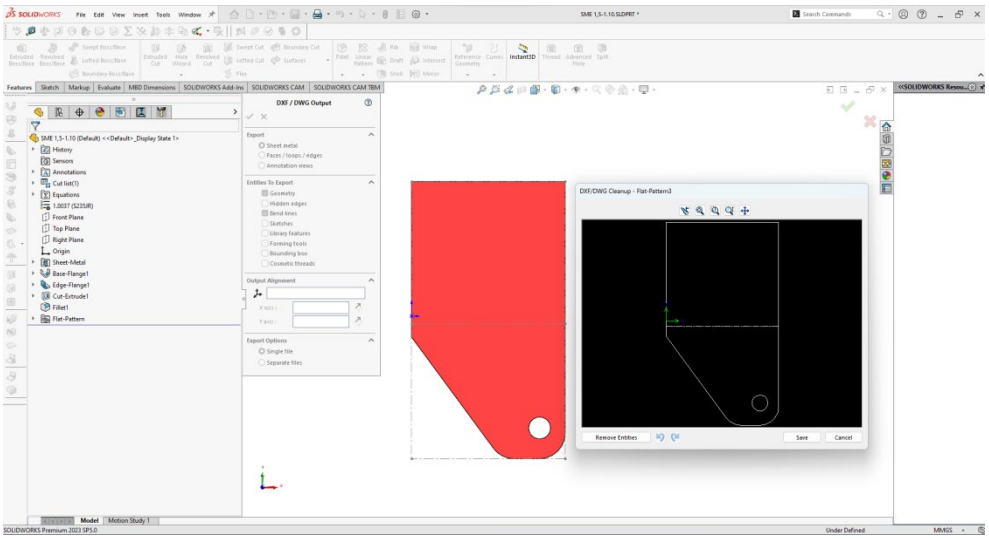

Fig. 6 - DXF file generated for CNC programming of the punching operation

Punching was performed on the ALPHA-CADMAN 1012T machine, first creating the inner hole and then the outer contour, according to the CAM simulation to avoid errors and collisions. CNC bending was carried out on the PPEB-4 C with a 90° angle and optimal processing parameters, verifying the accuracy of the angle and the alignment of the hole.

Following the correct sequence of operations – punching followed by bending – was essential to maintain geometric accuracy and prevent sheet metal deformations.

For the fabrication of the 10 mm thick sheet metal part with holes arranged on two concentric circles, the cutting and drilling operations were carried out using the Laser FC 1530-S CNC. The CAD model of the part is shown in Figure 7, and the 2D DXF file used for CNC programming is presented in Figure 8.

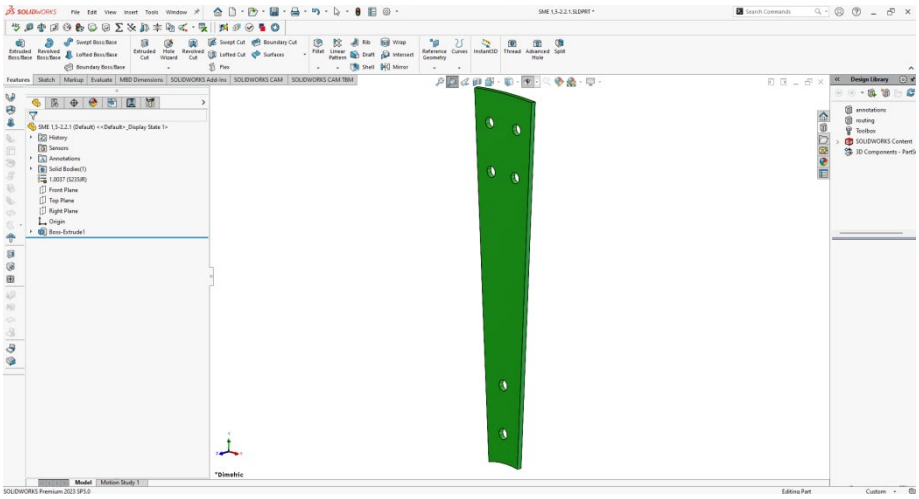

Fig. 7- CAD model of the 10 mm thick sheet metal part, with holes arranged on two concentric circles

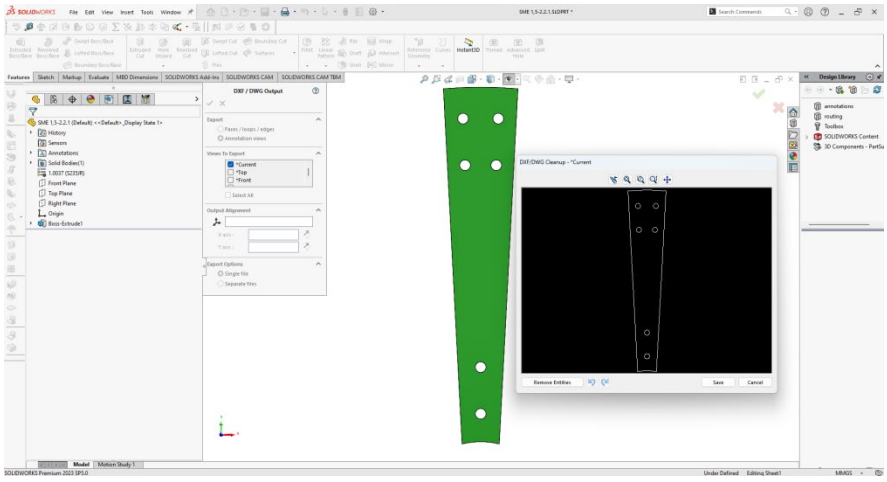

Fig. 8 - DXF file generated for CNC programming of the cutting and drilling operations with the Laser FC 1530-S

The model was checked for geometric correctness and exported in DXF format for import into the laser's CAM software. In CAM, the cutting and drilling parameters were defined, and the operation sequence was set so that the inner holes were made before the outer contour, preventing material deformations. The process was virtually simulated, and subsequently the part was machined on the laser worktable. Aspects of the machine interface and the execution stages of the part are shown in Figure 9.

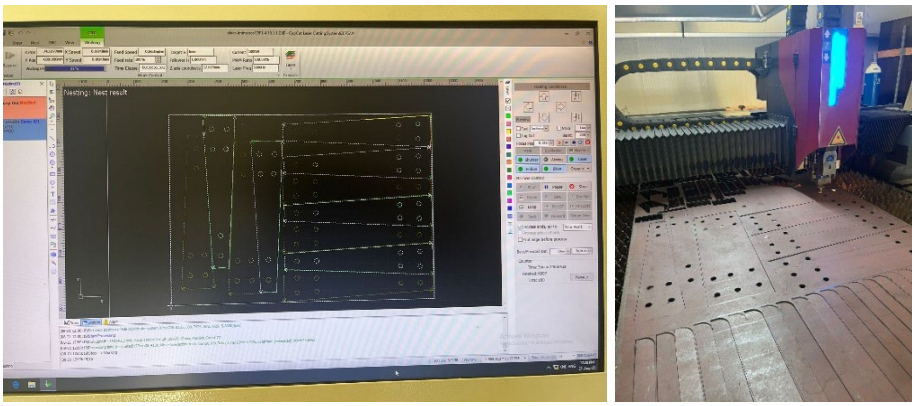

Fig. 9 - Aspects of the CAM software interface and the part execution on the Laser FC 1530-S CNC worktable

All parts were subjected to dimensional inspection on certified metrological equipment, confirming compliance with the project specifications. The accuracy of the holes, contour dimensions, and edge quality were evaluated, ensuring structural integrity and preparing the components for final assembly. Adherence to the operation sequence and CAM simulations prevented sheet metal deformations and guaranteed the precision of the parts, demonstrating the efficiency of the integrated CNC and laser methods for manufacturing components with complex geometry.

It is important to note that this work focuses on presenting the methodology for the design and fabrication of the SME 1.5-0 micro-hydro energy system. At this stage, no experimental tests regarding operational performance were conducted; the primary objective is to demonstrate constructural and technological feasibility, providing a methodological framework for future implementations in fish farms.

CONCLUSIONS

- The components of the *SME 1.5-0 Micro-Hydro Energy* experimental system were successfully manufactured using advanced CNC and CNC laser technologies, ensuring high precision.
- Following the operation sequence – cutting, punching/cutting → drilling → bending – was essential to prevent sheet metal deformations and maintain geometric tolerances.
- Dimensional inspection on certified metrological equipment confirmed that the parts complied with the project specifications, preparing them for the final assembly of the experimental system.
- The integration of CNC and laser technologies demonstrated the efficiency of producing complex components with precision, repeatability, and sustainability, highlighting the potential for applying these methods in micro-hydro energy systems and other industrial applications.

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PERFORMANCE EVALUATION OF THE EXPERIMENTAL PLANER-GRADER MODEL FOR PERMANENT GRASSLAND MAINTENANCE

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EVALUAREA PERFORMANȚELOR MODELULUI EXPERIMENTAL DE RINDEA-GREDER PENTRU ÎNTREȚINEREA PAJIȘTILOR PERMANENTE

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ABSTRACT

The paper presents the results of field testing under real operating conditions of an experimental planer-grader model designed for permanent grassland maintenance, developed within the ADER 15.3.2 project. The study focused on the machine's performance in destroying molehills on an experimental plot located in the Drăguș area (Brașov County, Romania). The research included the determination of pedoclimatic characteristics, soil resistance and moisture analysis, as well as the evaluation of energetic and operational indicators such as working speed, traction force and power, effective working capacity, and specific fuel consumption. The obtained results demonstrated the technical and functional efficiency of the equipment, confirmed by the final expert assessment that highlighted its reliability. The study concludes that the experimental planer-grader model represents a viable solution for permanent grassland maintenance works, contributing to environmental protection and biodiversity conservation.

REZUMAT

Lucrarea prezintă rezultatele testării, în condiții reale de exploatare, a modelului experimental de rindea-greder pentru întreținerea pajiștilor permanente, dezvoltat în cadrul proiectului ADER 15.3.2. Studiul a urmărit comportarea utilajului la lucrările de distrugere a mușuroaielor pe un lot experimental situat în zona Drăguș (județul Brașov). Cercetările au inclus determinarea caracteristicilor pedoclimatice, analiza rezistenței și umidității solului, precum și evaluarea indicatorilor energetici și de exploatare, cum ar fi viteza de lucru, forța și puterea de tracțiune, capacitatea efectivă de lucru și consumul specific de combustibil. Rezultatele obținute au demonstrat eficiența tehnică și funcțională a echipamentului, confirmată și prin expertiza finală, care a evidențiat fiabilitatea acestuia. Concluziile studiului arată că modelul experimental de rindea-greder reprezintă o soluție viabilă pentru lucrările de mentenanță a pajiștilor permanente, contribuind la protecția mediului și menținerea biodiversității.

INTRODUCTION

Grasslands are essential ecosystems representing up to 40% of its land area (*Petermann, J.S. & Buzhdygan, O.Y.,2021*), with a role in conserving biodiversity, maintaining soil fertility, protecting against erosion and capturing atmospheric carbon.

Grasslands, through the integration of grasses and legumes (*Li, Z. et al., 2024*), provide animal feed, raw material for agriculture and contribute to the ecological balance of rural areas.

By maintaining dense and diversified vegetation, grasslands support hydrological functions, reduce the risk of floods and contribute to the conservation of specific flora and fauna (*Jia, H. et al., 2025*).

Sustainable grassland management, where it is currently homogeneous, is an important first step towards improving multifunctionality at the landscape scale (*Richter, F. J. et al., 2024*) and can be achieved by monitoring the state of vegetation and soil, carrying out periodic maintenance work (destruction of weeds, mowing, scarification, fertilization), avoiding overgrazing and maintaining the balance between agronomic use and environmental protection (*Liu, K., & Shao, X., 2024*). These interventions prevent land degradation, loss of soil fertility and the emergence of invasive species, thus the grassland vegetation ecosystem can be protected, preserving its richness and diversity (*Zhang, L., & Li, J., 2024*).

The grassland planer-grader is used for cleaning annual and multi-annual weeds, removing solid manure and micro-leveling the land on degraded permanent grasslands (*Zimmer, A. et al., 2024*). The machine can be towed during work and semi-mounted during transport, providing flexibility and adaptability to different terrain conditions.

The main components of the planer-grader include: assembled frame, left leveling blade, right leveling blade, rear leveling blade, front disc battery, left and right side disc batteries, rear leveling blade lifting-lowering mechanism, hydraulic system, running gear and tow bar. The machine operates in aggregate with wheeled tractors with powers between 59 and 81 kW (80–100 HP), offering high performance and energy efficiency (*Mocanu, V. et al., 2019*).

The experimental model of the 2.0 m planer-grader, used with the New Holland TL100A tractor, was developed by ICDP Brașov (*Mocanu, V. et al., 2024*), and the field experiments for the performance analysis were carried out by the ICDP Brașov team, in collaboration with the INMA Bucharest team.

In the international context, there are several models of planers-graders specialized for the destruction of dunghills and the maintenance of grasslands (*Mocanu, V. et al., 2021*). For example, the Robert DBS Dung Spreader Harrow is equipped with 40 cm leveling blades, effective in destroying dunghills and evenly distributing organic residues on the surface of grasslands. It also includes 10 cm solid manure spreading blades for evening out the residues and flexible tines for aerating and regenerating the soil, allowing for efficient management of stubble and organic residues and helping to improve soil structure (Pasture harrow, dung spreader DBS (atelier-robert.be)).

Another example is the Mole Hill Destroyer, a machine dedicated to destroying molehills, which levels the ground and prevents damage to equipment. It has working widths of 3.05 m and 3.66 m, can be mounted on various types of harrows and is easy to use and maintain. Its efficiency in molehill management helps prevent damage to equipment and improve the quality of grasslands (molehilldestroyer.com). At the same time, the HE-VA Grass Rejuvenator is a multifunctional machine that includes cutting plates and ploughing blades for leveling molehills and rehabilitating grasslands. It has heavy-duty working rods for soil aeration and offers the possibility of adding a seeder for vegetation regeneration. Thus, the machine allows for efficient leveling of molehills and rehabilitating grasslands, contributing to increasing forage production (Grass Rejuvenator, level, scarify, reseed - HE-VA UK). The present study aims to analyze the performance of the 2.0 m experimental planer-grader model, used with the New Holland TL100A tractor, under real operating conditions, focusing on pedoclimatic characteristics, energy indices, working times and fuel consumption, providing useful information for sustainable grassland management.

MATERIALS AND METHODS

Within the Brașov ICDP, a technology was created to improve degraded grasslands by cleaning annual and multi-annual weeds, solid manure and micro-leveling the land with an experimental model of a 2.0 m grassland grader (fig. 1).

Fig. 1 - Experimental model of 2.0 m grassland grader planer

The operating principle is based on the combined action of the leveling blades and the rotating discs. During work, the tractor pulls the machine, and the left, right and rear leveling blades penetrate the surface layer of the soil to destroy annual and perennial weeds and level the land.

The adjustment of the depth and angle of the rear blade, carried out by the hydraulic lifting-lowering mechanism, allows the machine to adapt to different ground conditions and the degree of degradation of the meadow. The disc batteries, located at the front and sides, ensure the uniform breaking and distribution of organic residues and solid manure, contributing to the natural fertilization of the soil and stimulating the regeneration of vegetation. The undercarriage and the drawbar provide stability and maneuverability during work, and the assembled frame ensures the integration and rigidity of all components. Thus, the machine simultaneously combines land leveling, soil aeration, uniform spreading of manure and rehabilitation of degraded grasslands, reducing manual effort and preventing damage to both the land and the equipment.

This integrated operation makes the grader an essential tool for sustainable grassland management and increasing forage productivity.

Table 1 presents the main technical characteristics of the experimental model of the 2.0 m grassland grader planer.

Table 1

The main technical characteristics of the equipment used in the experiment

Characteristic	Value
Working width, [m]	2
Front disc battery	
- number of discs, [pcs.]	12
- disc diameter, [cm]	46
- disc type	dentate
Side disc battery	
- number of discs [pcs.]	4
- disc diameter [cm]	4
- disc type	sleek
Weight, [kg]	1613

The determination of the indices under operating conditions was carried out through experimental field research, on an experimental lot belonging to SC GUSUTRI COM SRL, a collaborating company of ICDP Brașov, located in Drăguș, Brașov County.

In April 2025, in Drăguș, Brașov County, average daytime temperatures were approximately 15°C, and nighttime temperatures around 3°C. Total precipitation was approximately 65 mm, distributed over 15 days, with an average humidity of 79% and wind with an average speed of 11 km/h.

Additional equipment used:

- to determine the degree of soil compaction, a Wile penetrometer was used, an instrument designed to measure soil resistance to penetration (*Ulanov, A. S.,et alea, 2024*). Measurements were made starting from 5 m from the end of the experimental plot and at different points separated in a diagonal direction towards the end;
- for direct measurement of water content, expressed as a percentage of the soil volume, the portable soil moisture meter Extech MO750 (*Hilal et al., 2022*). Soil moisture was determined at the same points where soil resistance to penetration was measured.

Table 2 presents the characteristics of the experimental field on which the experiments were carried out, with the experimental model of machine for overseeding degraded grasslands in aggregate with the TL 100A New Holland tractor.

Table 2

Characteristics of the experimental field

No.	Characteristic	Value
1	Soil type	brown
2	Degree of soil coverage with plants, [%]	70-80
3	Average plant height, [cm]	12
4	Plant mass, [g/m2]	100
5	Average soil moisture in the 0…10 cm layer, [%]	7,02
6	Penetration resistance in 10 cm layer, [MPa]	1,655

Calculation of the slippage δ of the drive wheels of the tractor from the TL 100A New Holland aggregate, slippage that occurs in the process of transmitting the tractor's traction power to carry out the working process of the experimental model, was calculated as follows:

- the slippage of the drive wheels was evaluated by comparing the number of rotations under load (Ns) with the number of rotations under load (Ng), according to the ISO/OECD standard 789-10:2006. The number of rotations under load was recorded separately for the left and right wheels, and the value used in the calculation was the arithmetic mean:

$$N_s = \frac{N_{sst} + N_{sdr}}{2} \quad (1)$$

- the number of idle revolutions was calculated based on the length of the test route (L=50 m) and the developed length of the tractor wheel (Lr):

$$N_g = \frac{L}{L_r} \quad (2)$$

- the slippage of the driving wheels was calculated according to the relationship:

$$\delta = \left(\frac{N_S - N_g}{N_S}\right) \times 100, [\%] \quad (3)$$

This method allowed the assessment of traction losses and the degree of slippage of the drive wheels.

The traction force was determined by the tensometric method using strain gauges, an acquisition system and a computer equipped with a specialized software package. The data that were stored were retrieved and processed by specialized software, after which the average values of the traction force were determined by eliminating the transition regimes during experimental research (*Matache et al., 2020; Persu et al., 2020*).

The traction power Ptr was calculated based on the travel speed vl and the traction force Ftr (*Marin et al., 2012*).

The determination of the exploitation indices (effective working time, time losses, effective working capacity and fuel consumption per hectare) of the experimental model of the overseeding machine in aggregate with the New Holland TL 100A tractor allowed the evaluation of the performance, which would ensure maximum economic effects in the concrete conditions of each farm (*Hunt, 2008*).

The determination of the fuel consumption per hectare was based on the direct measurement of the volume of fuel consumed, which consisted of completely filling the tank before the overseeding operation, carrying out the work on a determined area and finally filling the tank again and measuring the volume of fuel added (*Voicu et al., 2020*).

To ensure the reproducibility of the results, each experiment was carried out in 3 independent repetitions. The data obtained were statistically processed by calculating the mean, standard deviation and coefficient of variation, providing a measure of the variability and consistency of the results.

RESULTS AND DISCUSSION

The soil penetration resistance in the experimental plot was determined according to the procedure using a portable Wile penetrometer. The values obtained were 200 psi for the 0–10 cm layer, 220 psi for 10–20 cm and 240 psi for 20–30 cm. The superficial layer falls within the zone of good growing conditions, while the deeper layers show moderate compaction, which can limit root development and reduce water infiltration and gas exchange.

The average soil moisture, determined simultaneously with the penetration measurements, was 7.03%. Table 3 presents the average values of soil penetration resistance and soil moisture obtained from the measurements.

Table 3

Average values of soil characteristics of the experimental field

No.	Characteristic	Value
1	Average soil penetration resistance, [Kpa]	1517
2	Average soil moisture, [%]	7,03

The high resistance to penetration can be partly attributed to this low humidity. From a grassland management perspective, the results highlight the need for regular monitoring of soil compaction, especially after dry periods, and the application of light aeration or scarification work.

Table 4 presents the average values of the energy indices (average working speed and slippage of the tractor drive wheels of the aggregate) achieved for two speeds of the tractor in the aggregate.

Table 4

Average working speed and slippage of the tractor drive wheels in the aggregate

Speed level	Average speed of travel, [km/h]	Average slippage, [%]
V_1	5,25	11,13
V_2	5,91	10,88

The analysis of the results shows that, with the increase in travel speed, the slip of the drive wheels is slightly reduced, from 11.13% in gear V_1 to 10.88% in gear V_2.

This is explained by the increase in the dynamic stability of the aggregate and by a more uniform distribution of the load on the contact surface with the ground. The recorded values are below the threshold of 15%, considered optimal for surface agricultural work, which confirms good wheel adhesion and satisfactory efficiency of power transmission to the ground.

The determinations regarding the average working speed and the slip of the drive wheels of the tractor in the aggregate were carried out under real operating conditions, and Figure 2 shows an aspect of these measurements.

Fig. 2 - Appearance during measurements to determine the working speed and slippage of the tractor's drive wheels

The tensile force of the 2.0 m experimental planer-grader model was determined by the tensometric method, using 120 Ω strain gauges (type KFG-6-120-C1-11 N15C2) mounted on the tractor's drawbars and a QuantumX 1615 data acquisition system.

Figure 3 shows the materials and equipment used to determine the tensile strength.

Fig. 3 - Aspects during preparation for determining tensile strength

Table 5 presents the average values of working speed, tractive force (F_{tr}) and the calculated values of the required tractive power (P_{tr}) for the experimental model of a 2.0 m grassland planer-grader made for two speeds of the tractor in the aggregate.

Table 5

Average values of working speed, tractive effort and tractive power

Speed level	Working speed average		Average tractive force	Average tractive effort	
	[m/s]	[km/h]	[daN]	[CP]	[kW]
V_1	1,46	5,25	18450	35,88	26,39
V_2	1,64	5,91	18580	40,68	29,91

Table 6 presents the average values of the theoretical working capacity determined in two speed ranges for the experimental model of a 2.0 m planer-grader in aggregate with the New Holland TL 100A tractor on the experimental lot of SC GUSUTRI COM SRL located in Drăguș, Brașov County.

Table 6

Average values of theoretical work capacity

Speed level	Average working speed V_l	Average working width, B_l	Average theoretical working capacity, W_t
	[km/h]	[m]	[ha/h]
V_1	5,25	1,9	0,998
V_2	5,91	1,9	1,23

In the experiments under operating conditions carried out on an area of 0.3762 ha, the experimental model of a 2.0 m grassland planer-grader performed well throughout the period, under these conditions it achieved an operating safety coefficient of 0.96, an hourly performance capacity of 0.548 ha/h and a fuel consumption of 15.02 l/ha.

Figure 4 graphically presents the operating indices achieved during the tests.

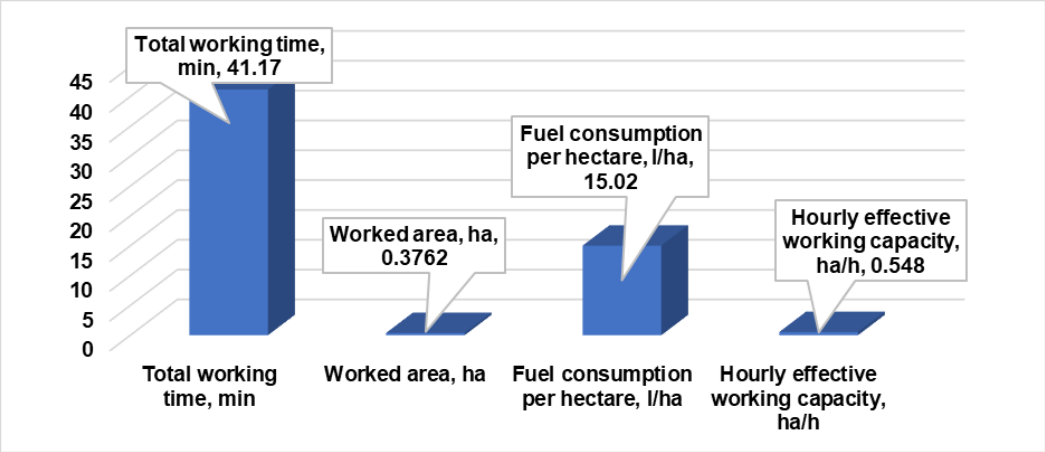

Fig. 4 - Operating indices achieved by the 2.0 m grassland planer-grader

Operating indices obtained:

- Total working time was 41.17 minutes (0.686 h).
- The achieved working capacity was 0.548 ha/h, which represents 50% of the theoretical capacity (1.10 ha/h).

Causes: Long times for turning, short length of the plot and the need for technical interventions.

- Consumption per hectare: 15.02 l/ha – is within normal limits for light work, without high resistance to advancement.

The energy efficiency and organization of the work were good, and time losses were moderate. The indicators obtained confirm that the assembly used is appropriate for this type of work, and productivity can be improved by reducing auxiliary times and combining work on larger areas.

Figure 5 presents some aspects before testing the experimental model of the 2.0 m meadow planer-grader (spring season).

Fig. 5 - Aspects before testing the experimental model of the 2.0 m meadow planer-grader (spring season)

Figure 6 presents some aspects after testing the experimental model of the 2.0 m meadow planer-grader (spring season).

Fig. 6 - Aspects after testing the experimental model of a 2.0 m meadow planer-grader (spring season)

CONCLUSIONS

- The experimental model of a grassland planer-grader for the maintenance of permanent grasslands, tested under real operating conditions on a 0.3762 ha plot in the Drăguș area (Brașov county), demonstrated very good operational performance and reliability.
- The effective working capacity obtained was 0.548 ha/h, representing approximately 50% of the theoretical capacity (1.10 ha/h), the difference being mainly determined by the turning times, the small plot size and the auxiliary adjustments made during operation.
- The specific fuel consumption was 15.02 l/ha, which is within normal limits for light plowing and maintenance of the grassland surface, confirming the energy efficiency of the machine.
- The equipment maintained good traction performance, with wheel slip values below 12%, ensuring efficient power transmission and minimal soil disturbance.
- The overall operational safety coefficient was 0.96, indicating a high level of functional reliability of the prototype grader-planer.
- Compared to other mechanized maintenance works (such as scarification or fertilization), the operation of the grassland planer-grader equipment offers a balanced ratio between fuel consumption and labor efficiency, ensuring both technical efficiency and environmental protection.
- The results obtained confirm that the experimental model of the 2.0 m grassland planer-grader represents a viable technological solution for the sustainable management and rehabilitation of permanent grasslands, contributing to increased productivity, soil protection and biodiversity conservation.

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SIMPLIFIED MODELING OF ACOUSTIC ATTENUATION FOR SOUND BARRIERS
/
MODELAREA SIMPLIFICATĂ A ATENUĂRII ACUSTICE PENTRU BARIERE SONICE

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Keywords: *sound barriers, acoustic attenuation, frequency variation.*

ABSTRACT
The paper presents a simplified calculation model for evaluating the acoustic attenuation of two constructive typologies of sound barriers, which highlights the differences in dB of the acoustic level at the receiver depending on the frequency variations. A comparative analysis is carried out for frequencies of 600 Hz, 1200 Hz, 2400 Hz, and 3600 Hz, depending on the distance between the sound barriers and the position of the receiver.

REZUMAT
Lucrarea prezintă un model de calcul simplificat pentru evaluarea atenuării acustice a două tipologii constructive de bariere fonice prin care se evidențiază diferențele în dB a nivelului acustic de la receptor în funcție de variațiile de frecvență. Se realizează o analiză comparativă pentru frecvențe de 600 Hz, 1200 Hz, 2400 Hz și 3600 Hz în funcție de distanța dintre barierele fonice și poziția receptorului.

INTRODUCTION

Noise pollution constitutes a significant environmental concern in urban areas, with road traffic identified as the predominant source. Approximately 70% of urban noise is attributable to transportation activities *(Medina, M. G. O. et al., 2010; Siano D., 2012),* underscoring its substantial contribution to ambient sound levels.

The public health implications of noise exposure are considerable. A report by the World Health Organization (WHO) indicates that Europeans collectively lose at least one million healthy life years annually due to diseases and disabilities induced by environmental noise, with road traffic noise being a primary contributor *(Fritschi, L.; Brown, L. et al., 2011; Gil-Lopez T. et al., 2017).* Beyond direct health impacts, noise pollution detrimentally affects various occupational and institutional settings, including schools, universities, offices, and hospitals, thereby compromising general well-being. For instance, in educational environments, elevated noise levels can disrupt teaching and learning processes by necessitating increased auditory effort in study spaces, potentially impairing concentration and academic performance.

Noise pollution pervades various occupational and institutional settings, including schools, universities, offices, and hospitals, thereby impacting working environments and overall well-being. In educational contexts, for instance, ambient noise can significantly disrupt pedagogical and learning processes, demanding increased auditory effort within study spaces *(Sala E, Rantala L., 2016; Silva LT, Oliveira IS, Silva JF., X)*.

Construction-generated noise represents another critical area of concern, primarily due to the elevated noise exposure levels experienced by workers *(Lee, S.C., et al., 2019; Li, X., et al.,).* This issue has gained amplified significance in recent years, driven by heightened environmental awareness within both the public and corporate sectors. Construction noise is known to induce *discomfort (Lee, S.C., et al.,; Liu, Y.; Xia, B. et al., 2017; Kwon, N. et al., 2018)* and can elicit adverse behavioral effects on surrounding communities. Furthermore, the effective control of on-site construction noise is inherently complex, compounded by several interacting factors: the ubiquitous presence and variability of noise sources, continuous logistical flows of materials, personnel, and vehicles, the inherent scale of construction sites, the limited efficacy of many attenuation solutions at lower frequencies, and the intrinsic difficulty in precisely evaluating the effects of implemented mitigation measures *(Sohrabi, S., Pàmies Gómez, T., & Romeu Garbí, J., 2020).* The modernization of road transport infrastructure has led to the construction of high-capacity

highways primarily designed to bypass residential areas. However, achieving this objective is not always feasible, particularly in regions experiencing intensive urban development where highways are often situated in close proximity to cities to facilitate convenient connectivity between urban and interurban traffic. Furthermore, the development of urban agglomerations along highway corridors can necessitate acoustic monitoring of these newly formed populated areas *(Enescu N., Vasile O.).*

Within the European Union, efforts to mitigate noise levels have been formalized through legislative frameworks. Notably, the EEC Machine Safety Directive of 1989, subsequently augmented by amendments in 1991 and 1993, established regulations pertaining to noise reduction *(Brooks B. M. et al., 1996).*

MATERIALS AND METHODS

In Figure 1, a thin, semi-infinite barrier is illustrated, characterized by a height *H*, with an acoustic source *S* located on the left side at a distance d_s from the barrier and 0,5 m above the ground. On the right side, the receiver *R* is positioned at height y_R and distance x_R. The source generates exclusively pure tones.

This study aims to evaluate the levels of acoustic attenuation achieved through the application of the Moreland–Musa method. The assessment will specifically focus on the spatial distribution of sound level reduction within the immediate proximity of a sound-absorbing panel.

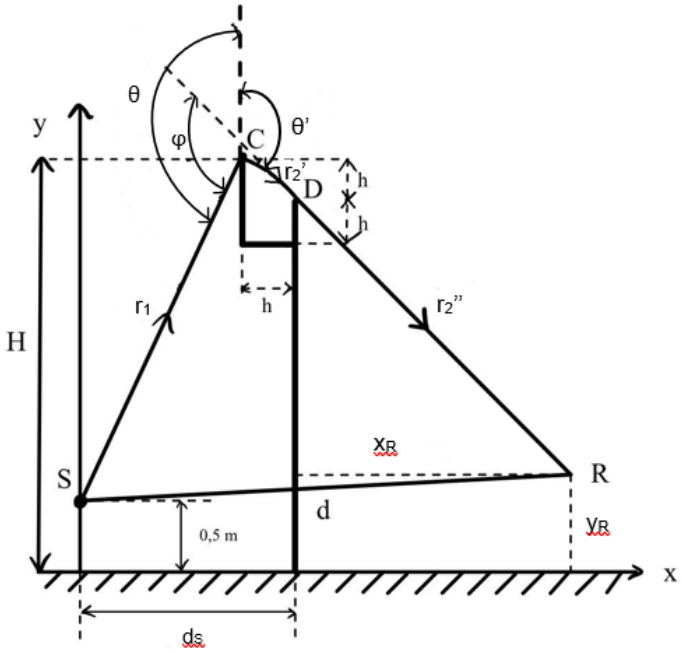

Fig. 1 - Barrier - variant 1

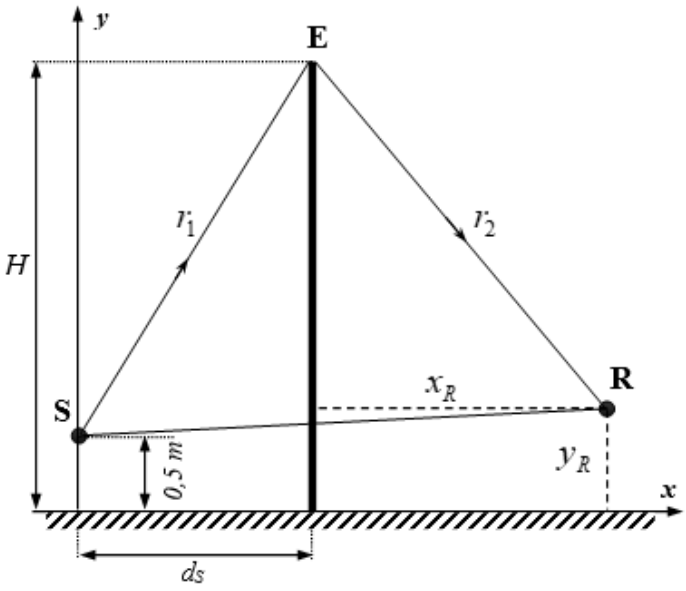

Fig. 2 - Barrier – variant 2

The fixed data are: H=4,6 m, h=0,3 m, d_s=3,2 m, which allows the determination of the coordinates of the points: S(0;0,5), D(3,2;4,3), C(2,9;4,6), and E(3,2;4,6).

In the first variant, based on the coordinates of points ***S***, ***D,*** and ***C*** relative to the axes of the considered system, the following distances are obtained:

$$r_1 = SC = \sqrt{(x_C - x_S)^2 + (y_C{}^2 - y_S{}^2)} = \sqrt{2{,}9^2 + (4{,}6 - 0{,}5)^2} = 5{,}02\,m \quad (1)$$

$$r_2{}' = CD = \sqrt{(3{,}2 - 2{,}9)^2 + (4{,}3 - 4{,}6)^2} = 0{,}42\,m \quad (2)$$

In the second approach, given the coordinates of points ***S*** and ***E*** with respect to the chosen reference system, the distance can be calculated as follows:

$$r_1 = SE = \sqrt{3{,}2^2 + (4{,}6 - 0{,}5)^2} = 5{,}2\,m \quad (3)$$

The receiver ***R*** coordinates are comprised in the intervals: $x_R = [3{,}5 \ldots 32]$, $y_R = [1 \ldots 4]$, distances are in meters.

The attenuation was determined using a computational program, with discretization intervals of ***Δx*** = 0,5 m along the *Ox* direction and ***Δy*** = 1 m along the *Oy* direction.

Since the magnitude of the attenuation depends on the sound frequency, calculations were carried out for four distinct frequencies: f = *(600, 1200, 2400,* and *3600) Hz*, as the noise exhibits a continuous distribution over the entire frequency range.

The Moreland–Musa formula, applied for the calculation of the attenuation in the first approach, is given below:

$$A = 10 \log\left\{3 + \frac{10}{\pi} k[(r_1 + r_2{}' + r_2{}'') - d]\right\} \text{ [dB]} \quad (4)$$

$$r_2{}'' = DR = \sqrt{(x_R - d_S)^2 + (y_R - H + h)^2} \text{ [m]} \quad 5)$$

and in the case of the second variant is:

$$A = 10 \log\left\{3 + \frac{10}{\pi} k[(r_1 + r_2) - d]\right\} \text{ [dB]} \quad (6)$$

$$r_2 = ER = \sqrt{(x_R - 3{,}2)^2 + (y_R - 4{,}6)^2} \text{ [m]} \quad (7)$$

For these cases, we compute the distance $d$using the next equation:

$$d = \sqrt{x_R{}^2 + (y_R - 0{,}5)^2} \text{ [m]} \quad (8)$$

k - wave number, *k=f/c*, where *f* is the sound frequency, and $c = 344$ m/s, represents the standard speed of sound.

RESULTS

In variant 1, due to the shape of the upper barrier, an additional reduction occurs caused by the diffraction phenomenon, which adds to the decrease calculated using equation (4). This additional reduction is determined through the supplementary damping factor *E*, whose value depends on the width *h* of the barrier and the angles *θ* and *θ'*.

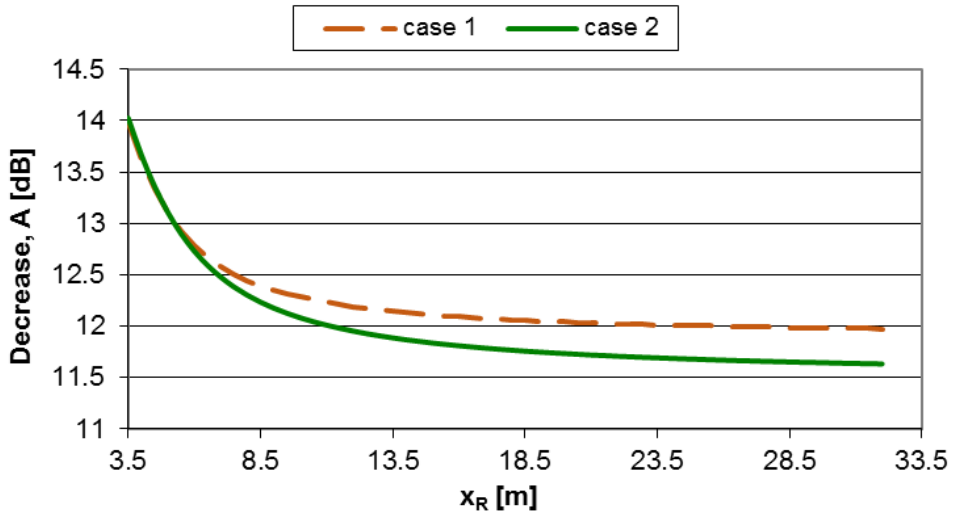

Fig. 3 - Representation of the decrease at 600 Hz for y_R=2m

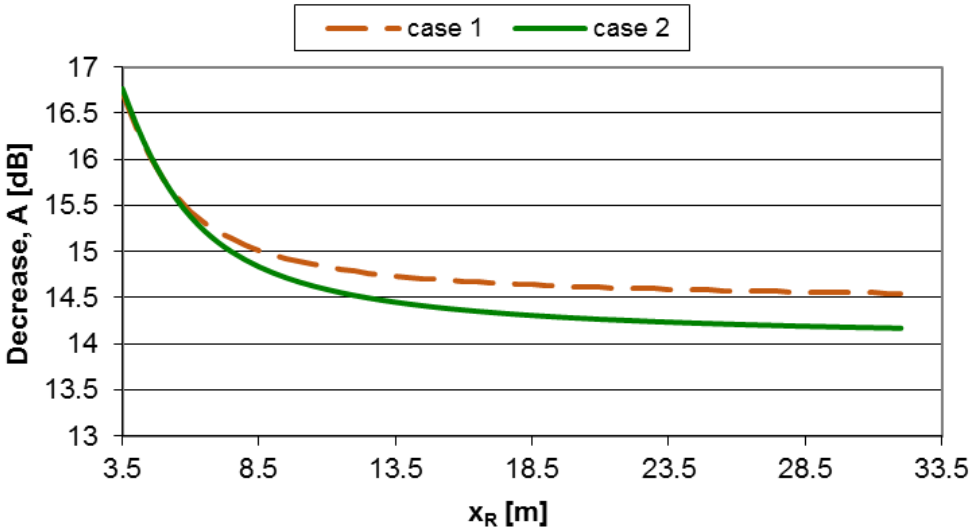

Fig. 4 - Representation of decrease at 1200 Hz for y_R=2m

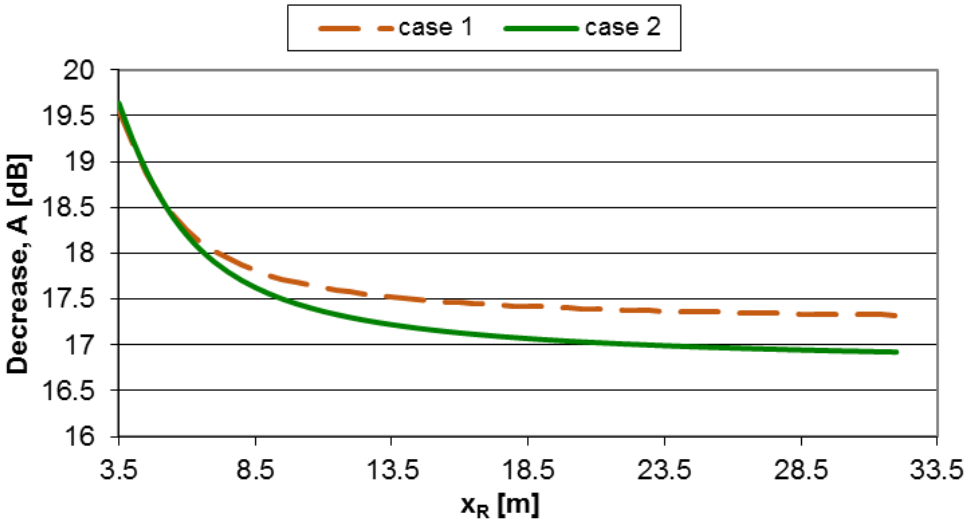

Fig. 5 - Representation of decrease at 2400 Hz for y_R=2m

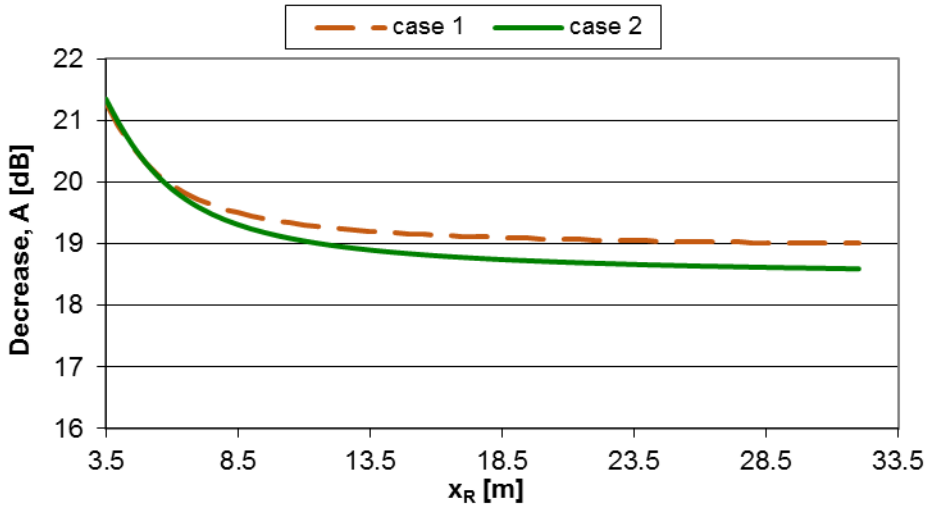

Fig. 6 - Representation of decrease at 3600 Hz for y_R=2m

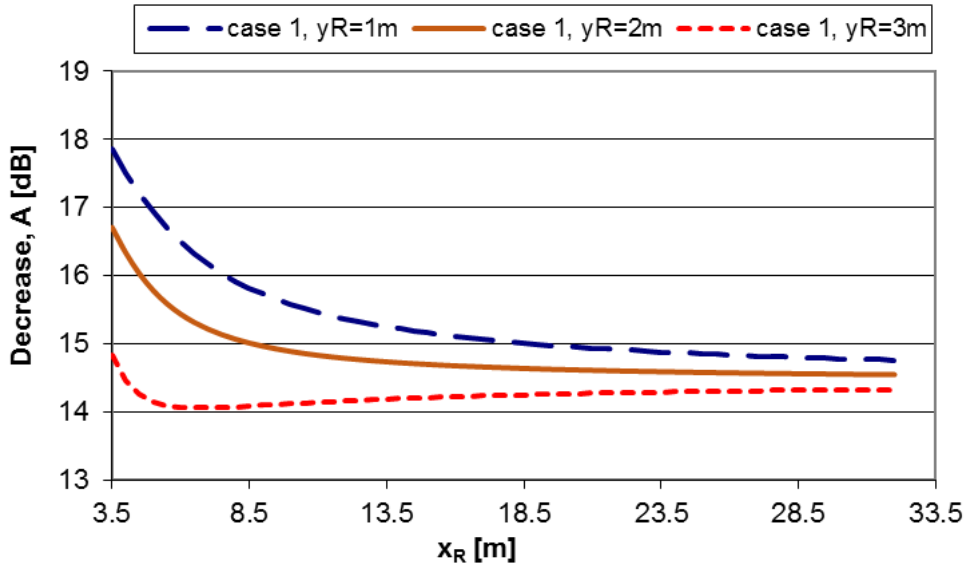

Fig. 7 - Representation of attenuation in case 1 for f=1200 Hz, y_R=1 m, y_R=2 m, y_R=3 m.

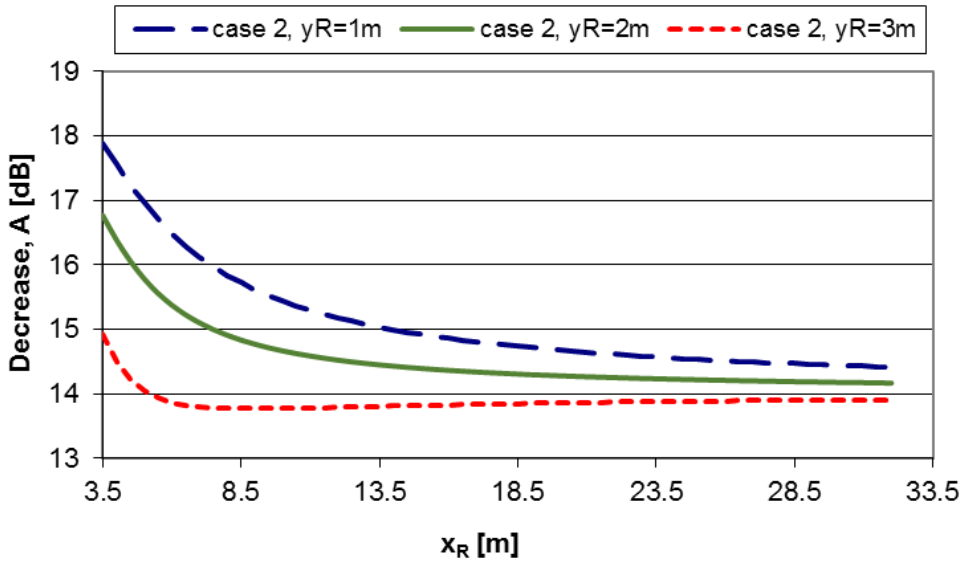

Fig. 8 - Representation of attenuation in case 2 for f=1200 Hz, y_R=1 m, y_R=2 m, y_R=3 m.

CONCLUSIONS

Analyzing the results presented in Figures 3–5, it can be observed that the attenuation produced by the barrier increases with frequency, confirming that acoustic barriers are more effective for higher noise frequencies. In variant 1, due to the shape of the upper part of the barrier, an additional reduction in sound level occurs, caused by the diffraction phenomenon, which adds to the attenuation calculated using the theoretical relation. This difference is quantified by the supplementary damping factor $\boldsymbol{E}$, which depends on the width h of the barrier and the angles of incidence $\boldsymbol{\theta}$ and $\boldsymbol{\theta'}$.

The graphs show that at short distances from the barrier, the variation in attenuation is more pronounced, while at larger distances the values tend toward a constant limit. Furthermore, the position of the receiver $\boldsymbol{y_R}$ slightly influences the attenuation level, with higher values observed at lower heights. Comparing the two analyzed cases, it is evident that variant 1 generally provides higher attenuation, highlighting the importance of the barrier's geometric shape in controlling sound propagation.

The results confirm the significant role of diffraction in noise reduction and indicate that optimizing the upper profile of the barrier can lead to notable acoustic improvements without major structural modifications.

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ULTRASONIC ASSESSMENT OF MECHANICAL PROPERTIES IN ISOTROPIC AND ORTHOTROPIC MATERIALS

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EVALUAREA ULTRASONICĂ A PROPRIETĂȚILOR MECANICE ALE MATERIALELOR IZOTROPE ȘI ORTOTROPE

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ABSTRACT

Material characterization is a fundamental requirement across engineering and applied sciences, as the reliable knowledge of mechanical properties determines both design strategies and performance assessment. While classical methods have long been employed during early development phases, there is an increasing need for non-destructive techniques that can provide accurate and non-invasive evaluation suitable for real applications. This paper presents both theoretical considerations and experimental findings related to non-destructive testing methods applied to isotropic materials as well as to orthotrop materials. The experimental investigations are based on the analysis and overlapping of dispersion curves for isotropic media, which allow the extraction of relevant mechanical characteristics. In addition, a dispersion curve is also obtained for a carbon-epoxy plate, serving as a first experimental step for composites, although in this case no overlap with theoretical predictions is performed. Beyond the experimental results, the study emphasizes the importance of microstructural aspects in composites, such as the alignment of fibers, which strongly affect the observed mechanical response. The paper therefore presents relevant information on the mechanical properties of both isotropic materials and composites, contributing to the refinement of non-destructive testing methodologies adapted to different classes of materials.

REZUMAT

Caracterizarea materialelor reprezintă o cerință fundamentală în inginerie și științele aplicate, deoarece cunoașterea precisă a proprietăților mecanice influențează atât strategiile de proiectare, cât și evaluarea performanțelor. Dacă metodele clasice sunt utilizate frecvent în etapele inițiale, devine din ce în ce mai importantă aplicarea unor tehnici nedistructive, capabile să ofere rezultate precise și neinvazive, adecvate aplicațiilor reale. Lucrarea de față prezintă atât considerații teoretice, cât și rezultate experimentale privind metode de testare nedistructivă, aplicate materialelor izotrope și ortotrope. Investigațiile experimentale se bazează pe analiza și suprapunerea curbelor de dispersie pentru medii izotrope, metodă ce permite obținerea caracteristicilor mecanice relevante. În plus, este prezentată și o curbă de dispersie obținută experimental pentru o placă de carbon-epoxy, constituind un prim pas în direcția caracterizării compozitelor, însă fără realizarea unei suprapuneri cu rezultatele teoretice. Dincolo de aceste rezultate, studiul subliniază importanța aspectelor structurale ale compozitelor, precum alinierea fibrelor, care influențează direct comportamentul mecanic observat. Lucrarea furnizează astfel informații relevante privind proprietățile mecanice ale materialelor izotrope și ale compozitelor, contribuind la dezvoltarea unor metodologii nedistructive adaptate diferitelor categorii de materiale.

INTRODUCTION

The mechanical characteristics of materials represent a fundamental aspect in numerous engineering domains, as they directly influence both the design process and the long-term reliability of structures and devices. In the medical field, for instance, advanced knowledge of material properties is crucial for the development of prosthetics, implants, and biomedical devices, where compatibility with the human body and durability under cyclic loads are essential. In the aerospace and automotive industries, the characterization of materials determines the performance of fuselages, joints, and structural components, where lightweight yet resistant materials are required to ensure both safety and fuel efficiency. Similarly, in the agricultural sector, machinery components such as frames, cutting tools, or transmission elements rely heavily on materials with well-defined mechanical responses to withstand harsh environmental conditions and repeated mechanical stress. Beyond these domains, civil engineering, energy systems, and even consumer electronics increasingly depend on accurate material characterization to optimize functionality, reduce failures, and extend service life. Consequently, the development of reliable techniques for evaluating the mechanical characteristics of materials has become a priority in both research and industry, particularly when moving toward advanced materials such as composites, which introduce new challenges for testing and characterization *(Chulkov, Terekhin, & Dumansky, 2020).*

Real-time characterization of materials has gained increasing importance, as the mechanical characteristics of engineering materials are not static but evolve over time due to processes such as aging, fatigue, environmental exposure, and operational stresses. These changes can significantly alter the structural integrity and functional performance of components, particularly in safety-critical applications such as aerospace, medical implants, or energy systems. Traditional destructive testing methods, while effective for initial evaluations, cannot capture these time-dependent variations during service life, nor can they be applied to components already integrated into complex systems. For this reason, non-destructive characterization methods are essential, as they allow continuous or periodic monitoring of materials without compromising their integrity. Such approaches provide valuable information on the degradation of mechanical properties, enabling predictive maintenance strategies, life-cycle assessment, and early detection of potential failures *(Qiu & Ge, 2025).* In addition, the integration of real-time non-destructive monitoring with advanced data processing and modeling techniques opens the possibility of adaptive control systems, where material behavior is continuously evaluated and compensated for during operation. This paradigm not only enhances safety and reliability but also contributes to cost reduction by minimizing downtime and extending the effective service life of components and structures *(Alqurashi, Alver, Bagci, & Catbas, 2025)*.

The pulse-echo method is one of the most widely used techniques for material characterization, particularly in the case of isotropic materials. It is based on the principle of transmitting an ultrasonic pulse into the material and recording the reflected signal (echo) generated at interfaces or discontinuities. By measuring parameters such as the time-of-flight, amplitude, and frequency content of the reflected waves, it is possible to determine key mechanical characteristics, including elastic moduli, wave velocities, thickness, and the presence of defects such as cracks, voids, or inclusions *(Filho, Moreno, & Luso, 2022).*

The method is highly valued for its simplicity, relatively low cost, and ability to provide fast results with minimal preparation. Its applicability extends across a broad range of engineering fields, from aerospace to civil engineering, where it is routinely used for quality control, defect detection, and verification of uniformity in isotropic media. However, the reliability of the pulse-echo method decreases when applied to more complex materials, such as composites, where directional dependence and heterogeneous structures affect wave propagation and make the interpretation of echoes more challenging *(Shibata & Ishihara, 2001).* Despite these limitations, the pulse-echo technique remains a cornerstone of ultrasonic non-destructive testing and serves as a benchmark for the development of more advanced characterization *methods (Maiyena, Daud, & Ayop, 2025)*.

Another method addressed in this paper is based on ultrasonic guided waves and the interpretation of dispersion curves. In this approach, experimental dispersion data are compared with theoretical predictions, and the degree of overlap provides valuable insight into the mechanical characteristics of the material. In contrast to the pulse-echo technique, which is most effective for isotropic media, the dispersion curve method can be applied to a broader range of materials, including composites, where structural features significantly influence wave propagation. Previous research has demonstrated the reliability of this method for evaluating elastic properties and detecting defects, and likewise, the matching of experimental and

theoretical dispersion curves has been reported as a robust strategy for advanced material characterization *(Griguța & Predoi, 2021), (Mihai Valentin Predoi, 2022), (Griguța A. D., Predoi, Petre, & Rugină, 2025).*

In addition, guided-wave techniques present practical advantages, such as the ability to cover large areas with limited sensing equipment, making them particularly well suited for applications in structural health monitoring and long-term assessment of engineering components *(Griguța, Predoi, & Petre, 2023), (Jiang, et al., 2023).*

THEORETICAL ASPECTS

Fundamental theoretical aspects of wave propagation in isotropic materials are first outlined, followed by key considerations regarding Lamb wave propagation and the formulation of dispersion curves. Subsequently, Hooke's law is introduced for the case of orthotropic materials, from which the authors derive the rotation matrix applicable to laminated composites.

1. Isotropic materials

The constitutive relation may be written as:

$$\begin{bmatrix}\sigma_{xx}\\ \sigma_{yy}\\ \sigma_{zz}\\ \sigma_{yz}\\ \sigma_{xz}\\ \sigma_{xy}\end{bmatrix}=\begin{bmatrix}C_{11} & C_{12} & C_{12} & 0 & 0 & 0\\ C_{21} & C_{11} & C_{12} & 0 & 0 & 0\\ C_{21} & C_{21} & C_{11} & 0 & 0 & 0\\ 0 & 0 & 0 & C_{66} & 0 & 0\\ 0 & 0 & 0 & 0 & C_{66} & 0\\ 0 & 0 & 0 & 0 & 0 & C_{66}\end{bmatrix}\begin{bmatrix}\varepsilon_{xx}\\ \varepsilon_{yy}\\ \varepsilon_{zz}\\ \varepsilon_{yz}\\ \varepsilon_{xz}\\ \varepsilon_{xy}\end{bmatrix} \quad (1)$$

with,

$$C_{66}=\frac{C_{11}-C_{12}}{2} \quad (2)$$

where,

σ_{ii} - Normal stresses component of the stress tensor;

σ_{ij} - Shear stresses component of the stress tensor;

C_{11}, C_{12}, C_{21}, C_{66} - Elastic coefficients;

ε_{ii} - Normal strains of the elastic tensor;

ε_{ij} - Shear terms of the elastic tensor.

The relationships between the Lamé coefficients, Young's modulus, Poisson's ratio, and the elasticity coefficients can be expressed as follows:

$$C_{11}=\lambda+2\mu=\frac{E(1-\nu)}{(1+\nu)(1-2\nu)}$$
$$C_{66}=\mu=\frac{E}{(1+\nu)} \quad (3)$$
$$C_{12}=C_{21}=C_{11}-2C_{66}=\lambda=\frac{\nu E}{(1+\nu)(1-2\nu)}$$

where,

λ, μ - Lame coefficients;

E -Young modulus;

v - Poisson ratio.

The two bulk velocities of longitudinal and transversal wave are expressed with respect to the engineering constants as follows:

$$c_T=\sqrt{\frac{\mu}{\rho}}=\sqrt{\frac{C_{66}}{\rho}}=\sqrt{\frac{E}{2\rho(1+\nu)}}$$
$$c_L=\sqrt{\frac{\lambda+2\mu}{\rho}}=\sqrt{\frac{C_{11}}{\rho}}=\sqrt{\frac{E(1-\nu)}{\rho(1+\nu)(1-2\nu)}} \quad (4)$$

where,

ρ - density of the material.

Therefore, the engineering constants, Young Modulus and Poisson ratio may be expressed as:

$$E=\rho c_T{}^2\frac{3c_L{}^2-4c_T{}^2}{c_L{}^2-c_T{}^2},\nu=\frac{c_L{}^2-2c_T{}^2}{2(c_L{}^2-c_T{}^2)} \quad (5)$$

Furthermore, by particularizing the general wave equation for a thin plate, and by introducing the scalar and vector potential formulation together with the appropriate boundary conditions, the dispersion relations governing Lamb wave propagation can be derived as follows (Griguța & Predoi, 2021), for symmetric modes of propagation:

$$C_s(k_x,\omega) = 4k_x^2 k_{Tz} k_{Lz} \tan(k_{Lz} z) + (k_T^2 - 2k_x^2)^2 \tan(k_{Tz} z) = 0 \quad (6)$$

And for asymmetric modes of propagation:

$$C_a(k_x,\omega) = 4k_x^2 k_{Tz} k_{Lz} \tan(k_{Tz} z) + (k_T^2 - 2k_x^2)^2 \tan(k_{Lz} z) = 0 \quad (7)$$

where,

k_x - Wavenumber component in the propagation direction (x-direction);

ω - Angular frequency of the wave;

k_T - Transverse (shear) bulk wave number;

k_L - Longitudinal bulk wave number;

k_{Tz} - Vertical component of the shear wave vector;

k_{Lz} - Vertical component of the longitudinal wave vector;

z – Half thickness of the plate.

with,

$$k_x^2 + k_{Lz}^2 = k_L^2;\ k_x^2 + k_{Tz}^2 = k_T^2 \quad (8)$$

For the purpose of illustrating the dispersion characteristics of Lamb waves, an aluminum plate with a thickness of 3 mm was considered as the reference structure. The dispersion relations were evaluated and subsequently presented in separate plots corresponding to the symmetric and antisymmetric modes of wave propagation.

In the graphical results, it can be observed that new higher-order modes emerge progressively with increasing frequency. Each of these modes appears only above its respective cut-off frequency, below which propagation is not supported.

The fundamental modes (S0 and A0) are present from the lowest frequency range and display strong dispersive behavior, particularly the antisymmetric A0 mode at low frequencies. In contrast, higher-order modes (S1, A1, etc.) gradually become accessible as the excitation frequency increases, and they exhibit more complex propagation characteristics.

The dispersion curves were obtained through numerical computations carried out in MATLAB, which allowed for an efficient solution of the transcendental equations defining the Lamb wave modes.

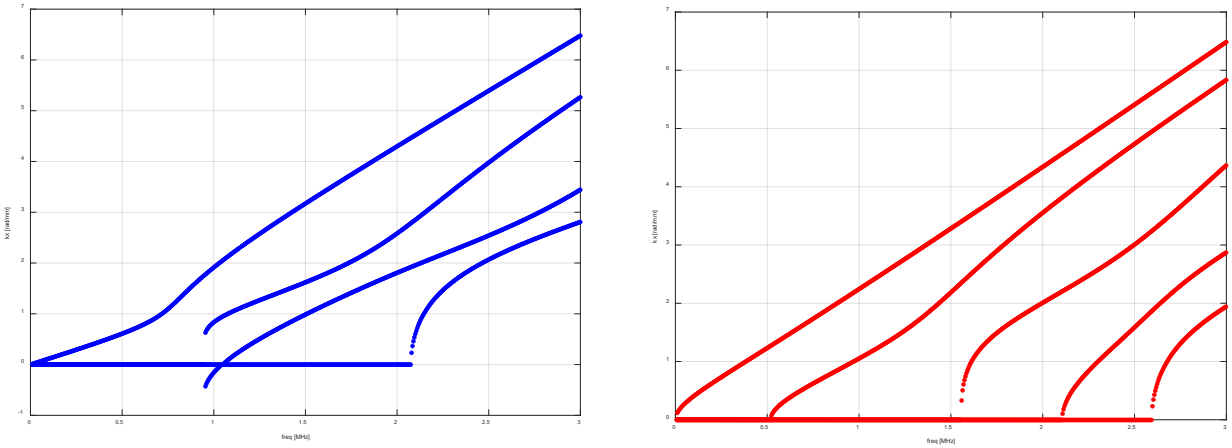

Fig. 1 - Dispersion curves for symmetric (blue) and antisymmetric (red) modes of propagation

2. Orthotropic materials

The constitutive relation for orthotopic materials with respect to elastic coefficients:

$$\begin{bmatrix}\sigma_{xx}\\ \sigma_{yy}\\ \sigma_{zz}\\ \sigma_{yz}\\ \sigma_{xz}\\ \sigma_{xy}\end{bmatrix}=\begin{bmatrix}C_{11} & C_{12} & C_{13} & 0 & 0 & 0\\ C_{21} & C_{22} & C_{23} & 0 & 0 & 0\\ C_{31} & C_{32} & C_{33} & 0 & 0 & 0\\ 0 & 0 & 0 & C_{44} & 0 & 0\\ 0 & 0 & 0 & 0 & C_{55} & 0\\ 0 & 0 & 0 & 0 & 0 & C_{66}\end{bmatrix}\begin{bmatrix}\varepsilon_{xx}\\ \varepsilon_{yy}\\ \varepsilon_{zz}\\ \varepsilon_{yz}\\ \varepsilon_{xz}\\ \varepsilon_{xy}\end{bmatrix} \quad (9)$$

For orthotropic materials, Hooke's law is formulated by explicitly accounting for the directional dependence of the material's elastic response. In this case, the engineering constants—namely the Young's moduli, shear moduli, and Poisson's ratios—are not isotropic but instead vary with respect to the three principal material axes. As a result, the constitutive relations involve different stiffness or compliance coefficients along each axis, leading to a more general representation of stress–strain behavior compared to the isotropic case.

Correlation between elastic constants and engineering constant is presented as:

$$C_{11}=\frac{(1-\nu_{yz}\nu_{zy})E_x}{\Delta};\ C_{22}=\frac{(1-\nu_{xz}\nu_{zx})E_y}{\Delta};\ C_{33}=\frac{(1-\nu_{xy}\nu_{yx})E_z}{\Delta}$$
$$C_{12}=\frac{(\nu_{xy}+\nu_{xz}\nu_{zy})E_x}{\Delta}=C_{21};\ C_{13}=\frac{(\nu_{xz}+\nu_{xy}\nu_{yz})E_x}{\Delta}=C_{31};$$
$$C_{12}=\frac{(\nu_{xy}+\nu_{xz}\nu_{zy})E_x}{\Delta}=C_{21};\ C_{13}=\frac{(\nu_{xz}+\nu_{xy}\nu_{yz})E_x}{\Delta}=C_{31}; \quad (9)$$
$$C_{23}=\frac{(\nu_{yz}+\nu_{yx}\nu_{xz})E_y}{\Delta}=C_{32};\ C_{44}=\mu_{yz};\ C_{55}=\mu_{xz};\ C_{66}=\mu_{xy}$$
$$\Delta=1-\nu_{xy}\nu_{yx}-\nu_{xz}\nu_{zx}-\nu_{yz}\nu_{zy}-2\nu_{xy}\nu_{yz}\nu_{zx}$$

Therefore, the general form of Hooke's Law with respect to engenerring constants looks like:

$$\begin{bmatrix}\sigma_{xx}\\ \sigma_{yy}\\ \sigma_{zz}\\ \sigma_{yz}\\ \sigma_{xz}\\ \sigma_{xy}\end{bmatrix}=\begin{bmatrix}\frac{1}{E_x} & -\frac{\nu_{yx}}{E_y} & -\frac{\nu_{zx}}{E_z} & 0 & 0 & 0\\ -\frac{\nu_{xy}}{E_x} & \frac{1}{E_y} & -\frac{\nu_{zy}}{E_z} & 0 & 0 & 0\\ -\frac{\nu_{xz}}{E_x} & -\frac{\nu_{yz}}{E_y} & \frac{1}{E_z} & 0 & 0 & 0\\ 0 & 0 & 0 & \frac{1}{\mu_{yz}} & 0 & 0\\ 0 & 0 & 0 & 0 & \frac{1}{\mu_{xz}} & 0\\ 0 & 0 & 0 & 0 & 0 & \frac{1}{\mu_{xy}}\end{bmatrix}\begin{bmatrix}\varepsilon_{xx}\\ \varepsilon_{yy}\\ \varepsilon_{zz}\\ \varepsilon_{yz}\\ \varepsilon_{xz}\\ \varepsilon_{xy}\end{bmatrix} \quad (10)$$

A compact form of the previous expression is:

$$\boldsymbol{\sigma}=\boldsymbol{C}\,\boldsymbol{\varepsilon};\ \boldsymbol{\varepsilon}=\boldsymbol{S}\,\boldsymbol{\sigma} \quad (11)$$

where,

σ, ε – Stress and strain tensor;

C, S – Stiffness matric and compliance matrix.

In the case of composite laminated materials, the orientation of each lamina plays a crucial role in determining the overall mechanical response of the laminate. A rotation of the individual layer with respect to the reference coordinate system significantly influences the stiffness properties and, consequently, alters the solution of the governing equations used in the computational analysis.

To correctly account for this effect, a transformation of the material property matrices is required. This is achieved by introducing a rotation matrix, which establishes the relationship between the local material axes of the lamina and the global coordinate system of the laminate The material principal axes of the lamina are assumed to be rotated by an angle θin the counterclockwise direction with respect to the global reference axes. This transformation enables the mapping of stresses and strains from the local

material coordinate system—where the material properties are defined—into the global coordinate system used for structural analysis.

The rotated stiffness matrix is computed by considering a transformation matrix for the strain and stress as follows:

$$[C'] = [T_\sigma]^{-1} \cdot [C] \cdot [T_\varepsilon] \tag{12}$$

with the corresponding transformation matrxis stress:

$$T_\sigma = \begin{bmatrix} cos^2\theta & sin^2\theta & 2sin\,\theta\,cos\,\theta \\ sin^2\theta & cos^2\theta & -2sin\,\theta\,cos\,\theta \\ -sin\,\theta\,cos\,\theta & sin\,\theta\,cos\,\theta & cos^2\,\theta - sin^2\,\theta \end{bmatrix} \tag{13}$$

and for strain:

$$[T_\varepsilon] = \begin{bmatrix} cos^2\theta & sin^2\theta & sin\,2\theta \\ sin^2\theta & cos^2\theta & -sin\,2\theta \\ -\frac{1}{2}sin\,2\theta & \frac{1}{2}sin\,2\theta & cos\,2\theta \end{bmatrix} \tag{15}$$

The authors have indicated that future research will extend the computational framework developed for orthotropic materials in order to present the theoretical dispersion curves corresponding to such media and to investigate, in greater detail, the influence of ply rotation on composite laminated structures. The incorporation of rotation effects is of particular significance, as it directly governs the directional stiffness and wave propagation characteristics of laminates.

MATERIALS AND METHODS

The determination of the mechanical properties of the examined material was carried out by employing two principal experimental approaches: the pulse–echo technique and the correlation of dispersion curves, established through the superposition of theoretical predictions with experimentally acquired data. The experimental configuration and the methodological procedures adopted in this investigation are succinctly outlined.

In the pulse–echo technique, the experimental configuration consists of a pulser–receiver, an oscilloscope, and an ultrasonic transducer. This method requires two distinct measurements in order to determine the full set of elastic engineering constants of the material, including Young's modulus (E), Poisson's ratio (ν), the shear modulus (G), the Lamé parameters (λ and μ, with μ = G), and the bulk modulus (K). Specifically, one measurement is performed with a longitudinal-wave transducer, while a second is carried out with a shear-wave transducer.

During the measurement, the transducer is excited by the pulser–receiver, generating an ultrasonic pulse that propagates into the specimen. The same transducer then acts as a receiver, detecting both the incident (direct) wave and its subsequent reflection after traversing the material. These signals are displayed on the oscilloscope as two distinct peaks corresponding to the forward and reflected waves, see Fig. 2. The time interval between the peaks represents the travel time of the ultrasonic pulse within the specimen. By repeating the procedure with both longitudinal and shear transducers, the respective wave velocities can be determined. These velocities are subsequently employed to calculate the complete set of elastic constants.

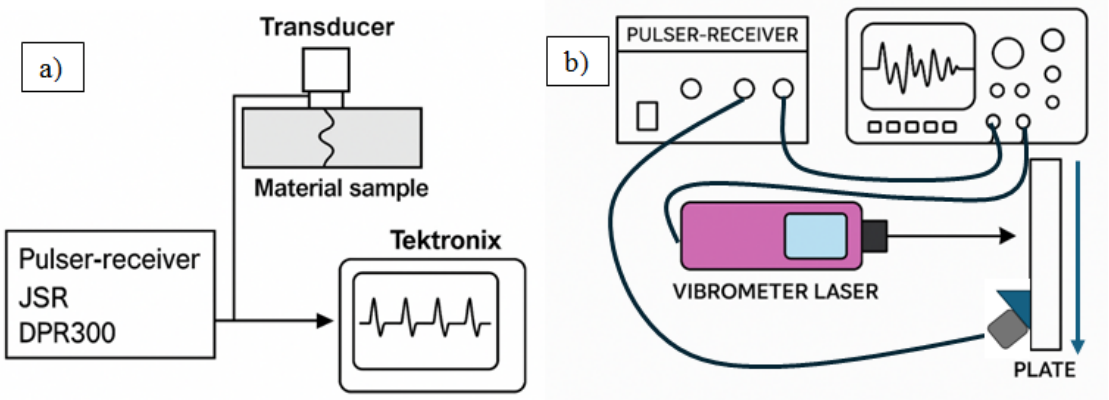

Fig. 2 - Experimental set up for a) pulse echo method b) overlapping of dispersion curves method

The previously described pulse–echo technique provides a relatively straightforward means of deducing the elastic characteristics of a material. Nevertheless, as emphasized earlier, its applicability is limited in the case of more complex materials. To address this limitation, a more sophisticated yet broadly applicable approach is employed, namely the comparison between theoretical and experimental dispersion curves. In this method, the dispersion relations predicted by theory are superimposed onto those extracted from experimental measurements, enabling a comprehensive characterization of the material.

As illustrated in Figure 2 b), the experimental arrangement comprises a pulser–receiver that excites an ultrasonic transducer, which in turn introduces a guided wave into a plate specimen. The out-of-plane surface displacements generated by the propagating wave are measured using a scanning laser vibrometer that records a spatial sequence of points along the plate surface. The positioning of the plate relative to the vibrometer is controlled with a precision displacement system. At each measurement point, the vibrometer output is directed to the oscilloscope, and the corresponding data are subsequently stored for post-processing. In order to efficiently couple the ultrasonic energy into the plate, the transducer is mounted on a polymethyl methacrylate (PMMA) wedge with an incidence angle of 30°, ensuring the correct excitation of guided modes

RESULTS

The experimental results are reported for two distinct specimens: an aluminum plate of 3 mm thickness, representing an isotropic benchmark material with well-established elastic constants, and a thin carbon/epoxy composite plate, selected as a representative complex material. The aluminum plate serves as a validation case, providing a straightforward comparison between experimental measurements and theoretical predictions.

By employing the pulse–echo technique, the authors applied the analytical formulations previously derived in this work in order to extract the elastic constants of the tested specimens. For the isotropic aluminum plate, the procedure yielded quantitative values for the principal engineering parameters, namely Young's modulus (E) and Poisson's ratio (v). The obtained results, 69.7 GPa for Young Modulus and 0.34 for Poisson ratio, serve both to validate the experimental methodology and to provide a direct comparison with reference values reported in the literature for aluminum alloys of similar grade and thickness.

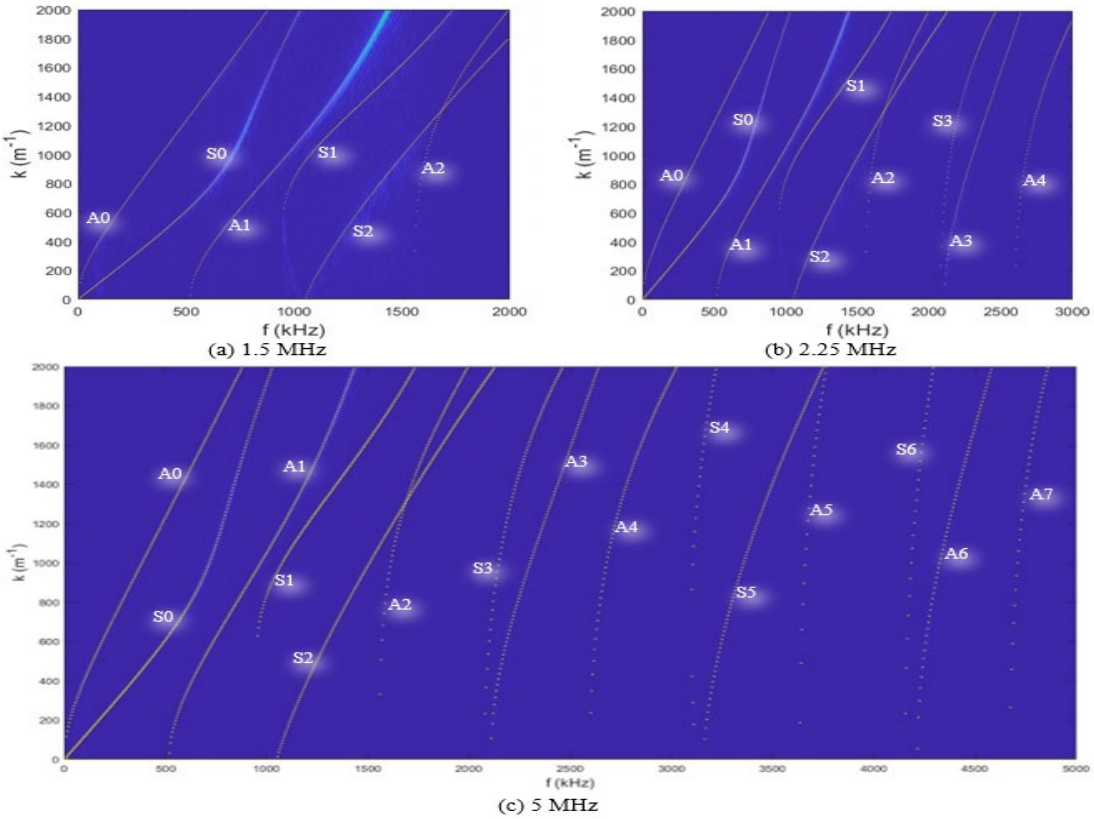

Fig. 3 - Overlapping of theoretical dispersion curves with experimental dispersion curves

(Griguta, et al., 2025)

The results obtained through the dispersion-curve overlapping method for the aluminum plate demonstrate an excellent agreement between the experimentally measured and theoretically predicted

curves see Fig. 3. The experimental campaign was carried out by the authors at the LOMC Laboratory, Le Havre, within the framework of an Erasmus+ collaboration. This high level of correspondence provides strong evidence that the material parameters employed in the theoretical modeling accurately represent those of the tested specimen. Consequently, the procedure confirms that the intrinsic elastic characteristics of the sample can be reliably inferred from the matching of theoretical and experimental dispersion curves.

For the composite specimen, only experimental results are reported, as the complex orthotropic behavior of the material renders the direct analytical derivation of dispersion relations non-trivial.

In this investigation, two excitation frequencies, namely 1 MHz and 1.5 MHz, were employed in order to capture the wave propagation response under different conditions and to enhance the robustness of the experimental observations. In the corresponding graphical representations, a dotted white line has been superimposed solely to facilitate the visualization of the experimental peaks and to guide the interpretation of the measured data, without implying any additional theoretical fitting, see Fig. 4.

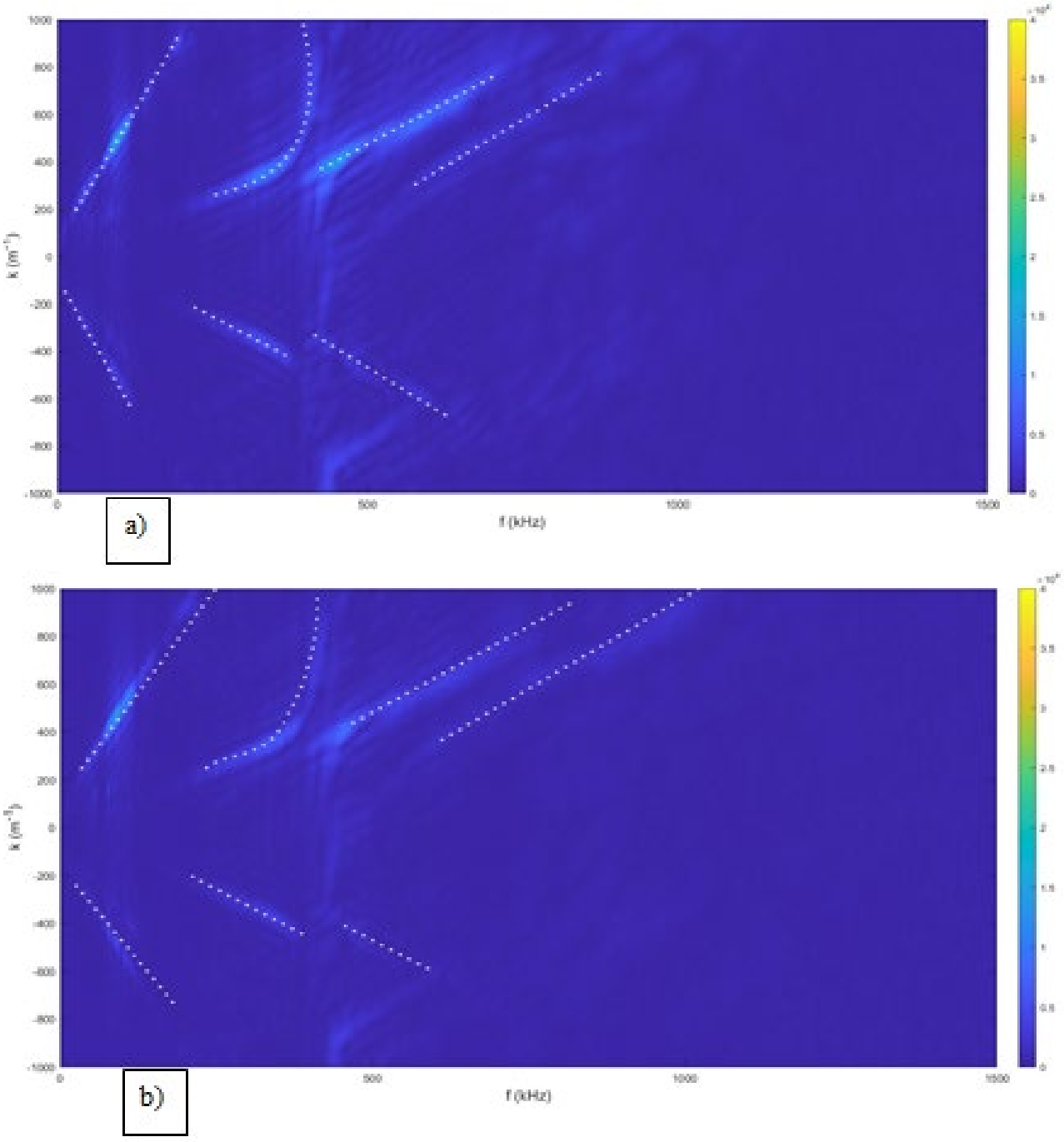

Fig. 4 - Experimental dispersion curves for carbon plate at a) 1MHz b) 2MHz

CONCLUSIONS

This study has presented the theoretical and computational understanding of guided wave propagation in both isotropic and orthotropic materials. By revisiting the governing equations for Lamb waves, the analysis has highlighted the fundamental differences between symmetric and antisymmetric modes of propagation, as well as their dependence on cut-off frequencies. The work has further addressed two nondestructive methods for determining the mechanical properties of materials: the pulse–echo technique, applied to an aluminum plate, and the dispersion curve matching approach, demonstrated through the superposition of theoretical dispersion curves for aluminum with experimentally obtained results for a carbon-fiber-reinforced composite plate. These complementary approaches have shown that guided waves represent a reliable and versatile means of characterizing both metals and composites.

At the same time, the results point toward several avenues for future research. In particular, while the overlapping of theoretical and experimental dispersion curves has been validated for aluminum, extending this procedure to orthotropic carbon-fiber laminates remains a necessary step to fully capture the effect of anisotropy and fiber orientation on wave propagation. Moreover, the computational framework for orthotropic materials requires completion through the incorporation of the rotation matrix formalism, which will allow the accurate treatment of arbitrarily oriented plies within laminated composites. Such an enhancement is essential for ensuring that the anisotropic stiffness contributions of individual layers are correctly represented in the global coordinate system and for improving the predictive capacity of the models.

Overall, the findings emphasize the importance of guided wave methods as nondestructive evaluation tools capable of bridging theory and experiment across a wide range of material classes. By extending the present framework to include complete orthotropic formulations and systematic experimental validation, future studies will strengthen the applicability of these methods in engineering practice, particularly in fields where the structural integrity of advanced composites is critical, such as aerospace, automotive, and civil infrastructure.

ACKNOWLEDGEMENT

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PM_{10} AND $PM_{2.5}$ PARTICLE POLLUTION IN TARGOVISTE CITY, DAMBOVITA COUNTY

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POLUAREA CU PARTICULE PM_{10} ŞI $PM_{2,5}$ ÎN ORAŞUL TÂRGOVIŞTE, JUDEŢUL DÂMBOVIŢA

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Keywords: *PM_{10}; $PM_{2.5}$; air pollution; portable device.*

ABSTRACT

Concentrations of suspended particles (PM_{10} and $PM_{2.5}$) were investigated in various urban and peri-urban areas, using localized measurements performed with the Lighthouse "Handy Man" portable device (Lighthouse Technologies, 2018) *(July-August 2024), supported by comparative data (Casella Microdust Pro)* (Casella, 2020)*. The aim was to identify primary pollution sources and assess the influence of meteorological conditions. The data reveal a persistent air quality problem* (Law no. 104/2011; Directive 2008/50/EC)*, with extremely high pollution peaks, far exceeding legislative limits and WHO recommendations* (Strop de aer, 2024; Vitalia Mediu, 2025) (Romanian language)*. The PM_{10} peak reached 904.35 µg/m³ (OMV Sârbi), and the $PM_{2.5}$ peak reached 80.82 µg/m³ (Zona Piața "1 Mai"). Critical episodes are correlated with heavy road traffic at peak hours, construction activities and dust resuspension. Dry weather and wind massively amplify concentrations, while rain provides only a temporary cleaning effect. The significant discrepancy between low averages and alarming highs underlines the episodic and localized nature of severe pollution. The results require the development of urgent strategies to monitor and manage local sources of dust and combustion.*

REZUMAT

Concentrațiile de particule în suspensie (PM_{10} și $PM_{2,5}$) au fost investigate în diverse zone urbane și periurbane, folosind măsurători localizate efectuate cu dispozitivul portabil Lighthouse "Handy Man" (Lighthouse Technologies, 2018) (iulie-august 2024), susținute de date comparative (Casella Microdust Pro) (Casella, 2020). Scopul a fost identificarea surselor primare de poluare și evaluarea influenței condițiilor meteorologice. Datele relevă o problemă persistentă a calității aerului (Legea nr. 104/2011; Directiva 2008/50/EC), cu vârfuri de poluare extrem de ridicate, depășind mult limitele legislative și recomandările OMS (Strop de aer, 2024; Vitalia Mediu, 2025) (Romanian language). Vârful PM_{10} a atins 904.35 µg/m³ (OMV Sârbi), iar vârful $PM_{2,5}$ a ajuns la 80.82 µg/m³ (Zona Piața "1 Mai"). Episoadele critice se corelează cu traficul rutier intens la ore de vârf, activitățile de construcție și fenomenul de resuspensie a prafului. Vremea uscată și vântul amplifică masiv concentrațiile, în timp ce ploaia oferă doar un efect temporar de curățare. Discrepanța semnificativă dintre mediile scăzute și maximele alarmante subliniază caracterul episodic și localizat al poluării severe. Rezultatele impun dezvoltarea unor strategii urgente de monitorizare și gestionare a surselor locale de praf și ardere.

INTRODUCTION

Air pollution with suspended particles (PM) represents a major risk for public health. *PM_{10}* particles (aerodynamic diameter ≤10 µm) and especially *$PM_{2.5}$* (≤2.5 µm) can penetrate deep into the respiratory system and are associated with cardiovascular and respiratory diseases.

The objective of this study is to characterize the levels of PM_{10} and *$PM_{2.5}$* in an urban area (Targoviște), using rapid and localized sampling techniques with a portable device Lighthouse "Handy Man" *(Lighthouse Technologies, 2018)* and Casella Microdust Pro *(Casella, 2020)*.

By analyzing peak data and correlating them with meteorological conditions and the type of area, the aim is to identify critical sources of pollution and the environmental factors that amplify them.

MATERIALS AND METHODS

The measurements were mainly performed with the Lighthouse "Handy Man" particle counter *(Lighthouse Technologies, 2018),* a laser scattering-based instrument designed for rapid monitoring of PM_{10} and $PM_{2.5}$ concentrations. Comparative data (July 25 and August 2, 2024 and March−June 2025) were also taken from a Casella Microdust Pro device *(Casella, 2020),* which, although operating in a different period, confirms the nature and magnitude of the peak episodes.

The measurements were carried out between July 25 and August 2, 2024 and March-June 2025.

The meteorological conditions included:

- high temperatures (maximum 25.5 ^{0}C−35 ^{0}C).
- extreme weather events on July 25 (strong wind of 50−70 km/h, torrential rains, hail), followed by predominantly sunny and dry weather.
- in the following days, the lack of precipitation favored the resuspension and accumulation of pollutants *(InfoClima, 2025; Climate-ADAPT, 2025).*

RESULTS

1. Exceptional PM_{10} Peaks (Lighthouse "Handy Man")

Data analysis revealed PM_{10} concentrations that massively exceed the daily legal threshold of 50 µg/m^3 (Directive 2008/50/EC; Law no. 104/2011).

Table 1

Measured PM_{10} concentrations and identified possible emission sources

Location	Date	PM_{10} Value (µg/m^3)	Observations/Possible Causes
OMV Sârbi	01.08.2024	904.35	Exceptionally high value, indicating an intense local source (heavy traffic at the intersection, gas station, dust).
Vis-à-vis Crom Steel/NIMET SRL	01.08.2024	358.07	Influence of industrial/truck traffic and industrial area.
County Court Area	27.07.2024	253.71	Heavy traffic in a central area.
Under the pavcom bridge	28.07.2024	167.45	Heavy traffic junction.

The peak of 904.35 µg/m^3 at OMV Sârbi is almost 18 times higher than the daily legal limit (50 µg/m^3), highlighting the existence of local, short-term, highly polluting events.

2. Notable PM2.5 Peaks (Lighthouse "Handy Man")

Although most $PM_{2.5}$ values were below 15 µg/m^3, alarming peaks were also recorded (Table 2).

Table 2

Measured $PM_{2.5}$ concentrations and identified possible emission sources

Location	Date and Period	$PM_{2.5}$ Value (µg/m^3)	Observations/Possible Causes
1 Mai" Square	29.07.2024 (morning)	80.82	Extremely high value, suggesting combustion sources (rush hour traffic, possible uncontrolled burning) and/or morning thermal inversion.
Teiș Area	30.07.2024 (seara)	43.49	Associated with nocturnal atmospheric stability and evening traffic.

The peak of 80.82 µg/m^3 exceeds the WHO recommended daily limit (15 µg/m^3*) (Strop de aer, 2024; Vitalia Mediu, 2025)* (Romanian language) by more than five times, confirming a serious health risk from point exposures.

3. Correlation of weather-pollution and predominant sources

The correlation of data confirms a dual role of meteorological factors:

- Cleaning effect of rain: decrease in PM concentrations observed after precipitation (e.g.: June 9, 2025, afternoon).
- Amplification of pollution: lack of rain and strong wind lead to massive resuspension of dust from roads and construction sites (e.g.: Peak of 1715 µg/m^3 PM_{10} on Cernăuți Street, March 28, 2025*) (InfoClima, 2025)* (Romanian language).

Predominant sources of pollution:

- Road Traffic: constant source of pollution, with clear peaks during peak hours (Calea Domnească, roundabouts).
- Construction/Construction Sites: confirmed by massive peaks of PM10 in Micro 2/Str. Cernăuți and Vulcana Pandele (heavy equipment traffic).
- Combustion: suggested by very high peaks of PM2.5 (Piața "1 Mai", “Groapa de Gunoi”), indicating combustion processes (traffic, uncontrolled fires).

4. Interpretation of the discrepancy between average vs. maximum values

The collected data (including the comparative ones collected with the Casella device) (Casella, 2020) show a major discrepancy between the average values (sometimes very low) and the instantaneous maximum values (extremely high).

For example, on Cernăuți Street (March-June 2025), maximums of 1099 µg/m^3 PM_{10} were recorded, although the corrected averages were only 1 µg/m^3. This indicates that severe pollution problems are predominantly episodic and localized, being triggered by the interaction between a strong local source (construction site, machinery traffic) and a favorable meteorological factor (wind that resuspends dust, lack of rain).

CONCLUSIONS

The study confirms a critical and persistent air quality problem in Targoviște, with numerous episodes of PM_{10} and $PM_{2.5}$ pollution that far exceed national legal limits (Law no. 104/2011; Directive 2008/50/EC) and, especially, WHO guidelines (Strop de aer, 2024; Vitalia Mediu, 2025).

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OPTIMIZING PROCESSES IN AGRICULTURE AND THE FOOD INDUSTRY
/
OPTIMIZAREA PROCESELOR ÎN AGRICULTURĂ ȘI INDUSTRIA ALIMENTARĂ

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Keywords: *artificial intelligence, models, sensors, information, optimization*

ABSTRACT

Against the backdrop of global food security issues, influenced by phenomena such as population expansion, climate change, limited resources and geopolitical instability, factors that will generate a significant increase in the need for food, it is necessary to widely adopt digital innovation in agriculture, often referred to as "smart agriculture". By introducing artificial intelligence into agricultural systems, processes in agriculture and the food industry can be optimized, which implies improving efficiency and productivity through the use of advanced technologies and sustainable practices. In this paper, forecasting models and sensors used in agriculture were briefly presented, with an in-depth study of the most common devices, where the focus was on the benefits and limitations of these equipment in order to form a concise representation for stakeholders. Optimizing processes in agriculture and the food industry can lead to increased competitiveness, reduced costs and improved product quality, thus contributing to food security and sustainability.

REZUMAT

Pe fondul problemelor legate de securitatea alimentară la nivel global, influențată de fenomene cum sunt expansiunea populației, schimbările climatice, resursele limitate și instabilitatea geopolitică, factori ce vor genera o creștere semnificativă a nevoii de alimente, este necesară adoptarea pe scară largă a inovației digitale în agricultură, deseori denumită „agricultură inteligentă". Prin introducerea inteligenței artificiale în cadrul sistemelor agricole se pot optimiza procesele în agricultură și industria alimentară, ceea ce implică îmbunătățirea eficienței și productivității prin utilizarea tehnologiilor avansate și a practicilor durabile. În această lucrare au fost prezentate succint modele de prognoză și senzori utilizați în agricultură fiind aprofundat studiul asupra celor mai uzuale dispozitive unde s-a pus accentul pe beneficiile și limitările acestor echipamente pentru a forma o reprezentare cât mai concisă pentru părțile interesate. Optimizarea proceselor în agricultură și industria alimentară poate duce la creșterea competitivității, reducerea costurilor și îmbunătățirea calității produselor, contribuind astfel la securitatea alimentară și sustenabilitate.

INTRODUCTION

The concern about global food security is an extremely sensitive issue, influenced by several factors, including population expansion, climate change, limited resources and geopolitical instability *(Dahlberg, K., 2012)*. With the world population estimated at 9.7 billion by 2050, there will be a significant increase in the need for food, which will put enormous pressure on agricultural systems. In addition, climate change poses a threat to agricultural production, giving rise to severe weather events, changing the timing of growing seasons and damaging natural resources such as soil and water *(Alexandratos, N. and Bruinsma, J., 2012)*.

Digital innovation in agriculture, often referred to as "smart agriculture" or "agriculture 4.0," integrates advanced digital tools and technologies into traditional agricultural practices. The exact origin of the term "smart agriculture" is difficult to trace, given that it emerged from the collective input of researchers and industry experts (Weraikat, D. et al, 2024). However, in the specialized literature, it is considered that precision agricultural technologies began to be used in the late 1980s in the United States and Australia *(Stafford, J., 2000)*.

Artificial Intelligence (AI), automation, and the Internet of Things (IoT) are useful for optimizing agricultural production and increasing sustainability. AI algorithms process data from various sources to help

farmers make informed decisions, while automated devices simplify planting, irrigation, and harvesting. IoT devices collect real-time data from sensors, drones, and other connected equipment, increasing operational efficiency *(Saiz-Rubio, V. and Rovira-Más, F., 2020; Friha, O. et al, 2021; Subeesh, A. and Mehta, C., 2021; Lakshmi, G. et al, 2023).*

One solution for transforming the agricultural sector is IoT-based automation for crop monitoring that includes a wireless sensor network (WSN) for real-time monitoring of crop health and a remote sensing platform for obtaining multispectral images for classifying healthy and unhealthy crops, which has led to increased production with reduced human effort *(Shafi et al, 2019).* Unmanned aerial vehicles (UAVs), used as remote sensing tools, provide aerial imagery that can detect problems early and apply precise interventions, optimizing resources and improving crop management *(Radoglou-Grammatikis, P. et al, 2020).*

An extremely important aspect is the monitoring and optimization of essential environmental and soil parameters (nitrogen (N), phosphorus (P), potassium (K), moisture and temperature), *(Macholdt, J. et al, 2019)* as well as a precise plant management strategy, focused on variable application of nitrogen fertilizers *(Weddell, B.J., 2023).* Regarding irrigation and efficient water management, an automatic irrigation system has been proposed, incorporating sensors for measuring pH, soil moisture and humidity. This system allows farmers to remotely access information from the field, reducing manual work and time, while improving productivity and resource use. The farmer is informed through a GSM (Global System for Mobile Communications) module, which allows real-time updates on field conditions via short message service (SMS), *(Pawar, R.Y. et al, 2021).*

An IoT-based soil nutrient system has also been integrated to help farmers make informed decisions throughout the agricultural process. The model incorporates sensors, cloud computing, and machine learning (ML) tools to collect real-time data on soil conditions and analyze nutrient levels *(Murali, K.S. et al, 2023).*

Another transformative potential of these technologies is how forecasting models can be used to improve both conventional and alternative agricultural systems. Exploring forecasting models can optimize food processing and supply chain management, thereby contributing to the resilience and sustainability of global food systems. Innovations in Food Security and Supply Chain Optimization take a comprehensive analytical approach to explore the integration of AI-based forecasting models in addressing key challenges related to global food security (fig. 1) *(Dhal, S.B. and Kar, D., 2024).*

Fig. 1 - Schematic diagram providing a comprehensive analysis of the challenges and constraints of global food security

(Dhal, S.B. and Kar, D., 2024)

By using artificial intelligence (AI), it is possible to optimize resource use, reduce waste, and minimize environmental impact *(Kennedy, N., 2024).* Data-driven insights help farmers understand the relationship between natural systems, which is essential for achieving both sustainability and food security goals *(Rozenstein, O., 2024).*

Optimization efforts in food processes have relied on simplistic, single-variable experimental approaches. These methods focused on evaluating the effect of a parameter at a given time on a given response, while holding all other factors constant. Although effective for certain scenarios, this approach introduced substantial limitations.

It neglected potential interactions between variables, which are often essential in understanding the complexity of food production systems *(Yolmeh, M. and Jafari, S.M., 2017).* Multi-objective optimization addresses problems that involve multiple responses or variables simultaneously, providing solutions that optimize multiple objectives simultaneously.

This approach is particularly relevant to food science, where competing objectives often require trade-offs *(Carrizosa, E.and Morales, D.R., 2013).*

MATERIALS AND METHODS

The focus of this paper is to assess the literature on advanced AI-based sensor technology that enables monitoring of critical environmental and soil parameters that affect crop yields, as well as forecasting models that can bring benefits to agricultural systems. In addition, through this paper, we aim to increase awareness of smart farming practices among farmers.

The literature suggests that collaboration between various stakeholders in the agricultural supply chain can lead to optimization of processes in agriculture, which produces numerous benefits, including increased efficiency and productivity, cost reduction, and improved product quality.

Artificial Intelligence-Based Forecasting Models

- **Crop Yield Predictions:** Models can predict crop yields with greater accuracy, enabling better planning and risk management *(Benami, E. et al, 2021; Kim, N. et al, 2019).*
- **Climate Monitoring and Real-Time Data:** Models help monitor and respond to changing weather patterns, providing farmers with real-time information to adjust their practices *(Singh, B. and Kaunert, C., 2024).*
- **Supply Chain Optimization:** Models provide optimization solutions for food supply chains by reducing inefficiencies, minimizing costs, and improving food accessibility *(El Jaouhari, A. and Hamidi, L.S.).*

Harnessing forecasting models

- **Climate forecasting models:** The effects of climate change, such as changes in growing seasons and severe weather conditions, pose significant risks to agricultural production. Climate forecasting models predict these changes in weather patterns and environmental changes, helping farmers adapt their practices to prevent crop failures and use resources more efficiently *(Kang, Y. et al, 2009).*
- **Crop yield forecasting models:** The increasing demand for food driven by population growth is putting immense pressure on agricultural systems. Crop yield forecasting models use data on soil quality, precipitation and temperature to predict yields, allowing for better planning and timely interventions to prevent shortages, ensuring food security *(Basso, B. and Liu, L., 2019).*
- **Supply chain forecasting models:** Inefficient distribution contributes to significant problems in food supply chains. Artificial intelligence-based supply chain forecasting models are essential in predicting customer demand, identifying logistical bottlenecks, and optimizing the transportation of food from producers to consumers, improving the operational efficiency of food distribution systems *(Abaku, E.A. et al, 2024).*

The Evolution of Alternative Agriculture and Food Processing in Agricultural Systems

- ***Hydroponics and Aquaponics:*** These soilless farming systems rely on precise control of environmental factors such as water, nutrients, and light. Forecasting models help predict ideal nutrient levels, water conditions, and energy use to optimize plant and fish growth, ensuring efficiency and consistency of yield *(Saikanth, K. et al, 2023; Sharma, N. et al, 2018).*
- ***Vertical Farming:*** Vertical farming offers a sustainable solution for food production in highly urbanized areas, but it is energy-intensive. Forecasting models help balance energy

consumption, optimize harvest cycles, and predict plant growth rates to enhance sustainability *(Beacham, A.M. et al, 2019; Kalantari, F. et al, 2018).*

- **Advanced Food Processing Techniques**:
  In food processing, predictive models, based on real-time data from Internet of Things (IoT) devices and automation, help improve product quality and safety. These models predict spoilage rates, optimize consumption, and ensure efficient processing workflow, leading to improved food quality and reduced waste *(Misra, N.N. et al, 2020; Gao, T. et al, 2020).* Modele esențiale de prognoză pentru optimizarea climei, randamentului și lanțului de aprovizionare
- ***Time Series Models***
  ARIMA and SARIMA are commonly used for yield and price forecasting in agriculture. These models analyze historical data to predict trends and cycles, helping farmers and policymakers make informed decisions about resource allocation *(Suresh, K.K. et al, 2011; Mila, F.A. and Parvin, M.T., 2019; Divisekara, R.W. et al, 2020).* These models also extend to processing programs to ensure that food products are optimally distributed to minimize waste (*Falatouri, T. et al, 2022).*
- ***Machine Learning (ML) Models***
  ML models, including RF and SVM, excel at handling complex, nonlinear relationships between climate, soil quality, and market conditions. These models are widely used for yield forecasting and market prediction, providing robust insights into market dynamics and resource optimization *(Kok, Z.H. et al, 2021; Suresh, N. et al, 2021).*
- ***DL Models***
  - LSTMs, a type of recurrent neural network (RNN), analyze sequential data, such as long-term weather patterns, enabling accurate predictions of environmental and agricultural system impacts *(Jaiswal, R. et al, 2022).*
  - CNNs process spatial data, such as satellite imagery, to monitor crop health and predict supply chain disruptions, providing real-time insights into potential bottlenecks *(Prashanthi, V. and Srinivas, K., 2020).*
  - Integrating LSTMs and CNNs into hybrid models improves prediction accuracy by combining spatial and temporal data, especially in advanced yield prediction and supply chain management *(Gafurov, A. et al, 2023; Suebsombut, P. et al, 2021; Iitsuka, S. et al, 2019).*
- ***The evolution of hybrid models in food security.***
  Hybrid models combine various forecasting methods, such as ML, DL, and time series models, to improve the accuracy of predictions in food systems. These models are especially valuable for addressing complex agricultural challenges.
  - Time series + ML: Combining time series with ML provides a comprehensive understanding of agricultural crop trends, increasing the accuracy of forecasts in terms of yield and prices *(Guo, Y., 2024; Özden, C., 2023).*
  - ML+DL: Hybrid models that combine ML for feature selection with DL for long-term predictions are particularly effective in forecasting complex risks such as pest outbreaks, extreme weather events, and supply chain failures *(Paul, R.K. et al, 2022; Khatraty, Y. et al, 2022).*
  - Clustering + ML: Recent research highlights the application of clustering algorithms with traditional ML models for improved sales prediction in retail environments. The same approach can be adapted to agriculture to group farms with similar environmental and economic characteristics *(Udokwu, C. et al, 2022).*

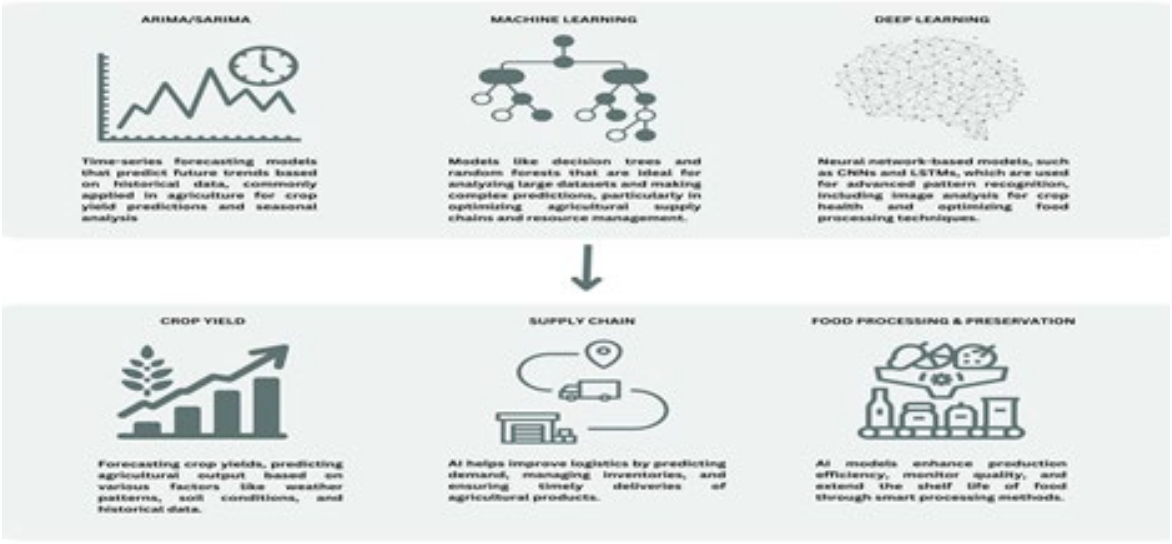

Fig. 2 - Applications of forecasting models based on artificial intelligence in agriculture
(Dhal, S.B. and Kar, D., 2024)

Sensors used in agriculture

In this paper, we present a single device that integrates multiple sensors to facilitate farmer interaction with technology. This approach eliminates the need for the farmer to implement four distinct sensors.

- **IP68 ABS Soil NPK Sensor Taidacent, B08MXXSP59, Guangzhou, China** (fig. 3), high-precision NPK sensor for soil nutrients, intelligent fertilizer detector, tester. Technical specifications: Measurement range: 0-1999 mg/kg; Working humidity: 5-95% (relative humidity), non-condensing; Measurement accuracy: ±2%F.s; Resolution: 1 mg/kg (mg/L); Working temperature: 5-45°C; Power supply: 12 V-24 V DC *(Amazon, 2024)*.
- **The ESP32 microcontroller (SIMAC Electronics HANDEL GmbH, Neukirchen-Vluyn, Germany)** (fig. 4) was used to develop the sensor system, which serves as the central processing unit for controlling the entire system. It incorporates the 5-pin NPK sensor to measure soil parameters such as potassium, phosphorus, moisture, temperature and pH levels. The system is equipped with Wi-Fi connectivity for real-time data transmission and includes local data logging on an SD card to ensure data backup in case of Wi-Fi instability *(McCormick, A., 2017)*.

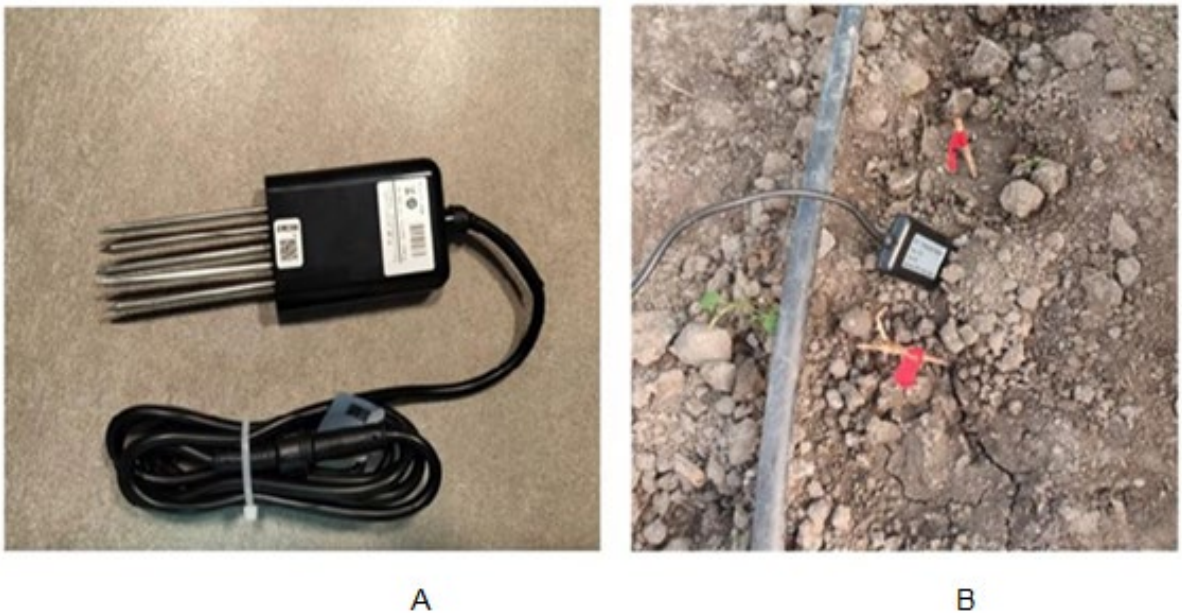

Fig. 3 - (A). A close-up view of the sensor. (B). The NPK sensor installed.
(Amazon, 2024)

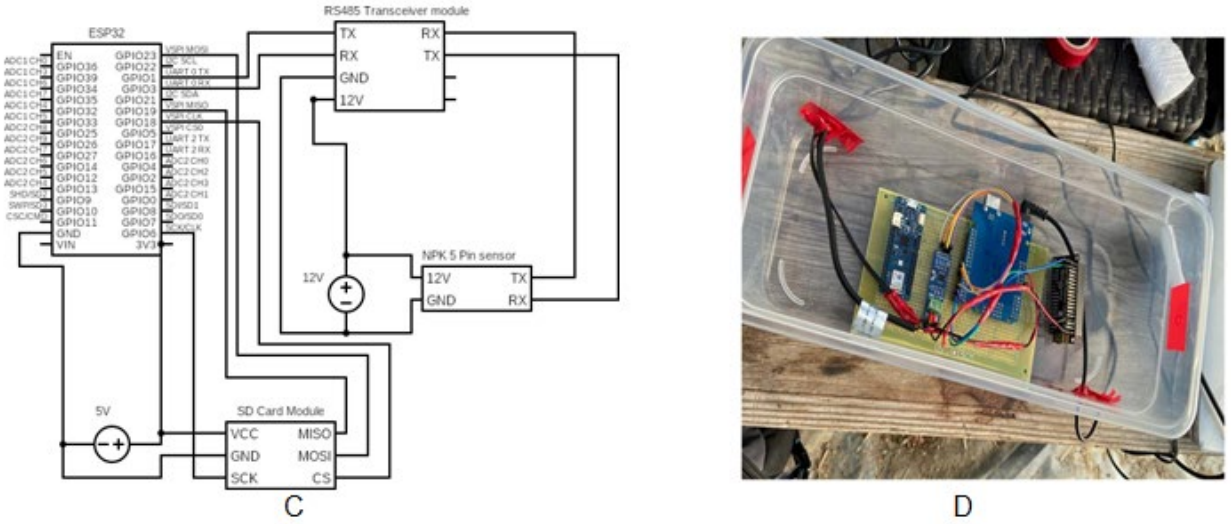

Fig. 4 - Schematic diagram of the system circuit (C) and the actual installed system (D).
(McCormick, A., 2017)

The data collection process was designed to capture comprehensive data on environmental and soil parameters across the entire site. Fig. 5 illustrates the flow chart of the steps involved in this process. The sensors continuously recorded data at set intervals (every 2 minutes) to capture sufficient variations and overall trends. The data was transmitted via Wi-Fi to a central database using IoT communication protocols. A data logger was also used as a backup plan to prevent data loss. The collected data was recorded in a cloud-based storage system, allowing remote access cloud, permițând accesul de la distanță *(Weraikat, D. et al, 2024).*

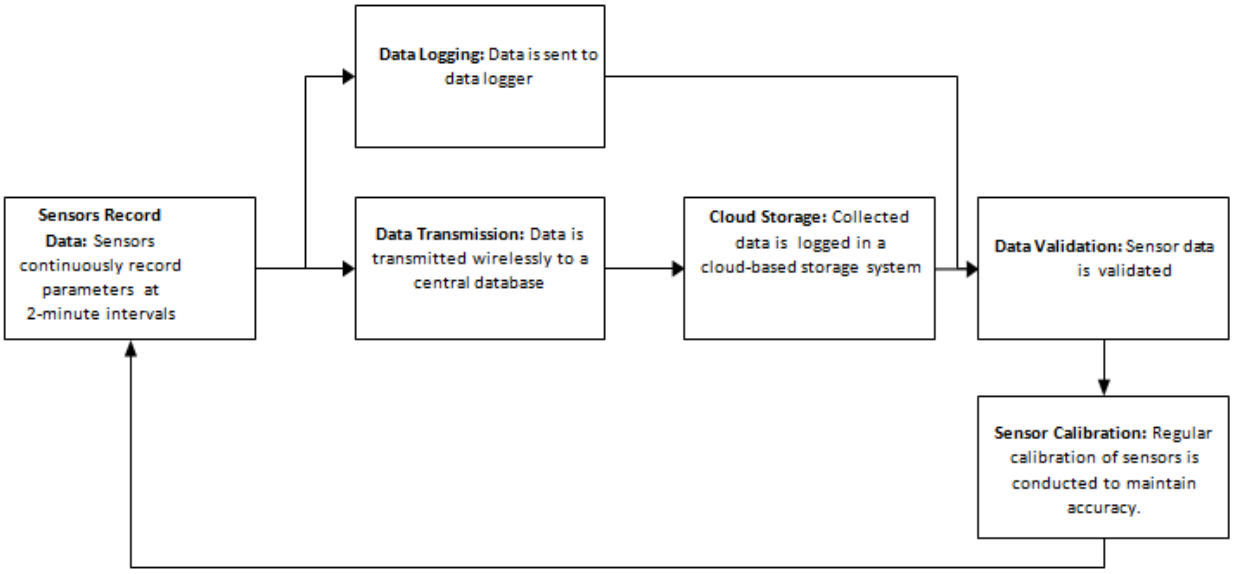

Fig. 5 - Data collection process for environmental and soil parameters.
(Weraikat, D. et al, 2024)

Multi-objective optimization (MOO)

Multi-objective optimization (MOO) is an important strategy to address the multiple challenges of the food industry. This sector operates at the confluence of numerous, often conflicting, objectives, such as economic profitability, nutritional quality, environmental sustainability, and alignment with global frameworks such as the United Nations 2030 Agenda for Sustainable Development. Multi-objective optimization (MOO) provides a structured methodology for balancing diverse objectives, providing a path to innovation, resilience, and sustainability in food production and distribution systems. Ecological sustainability and alignment with global frameworks such as the United Nations 2030 Agenda for Sustainable Development. MOO provides a structured methodology for balancing these diverse objectives, providing a path to

innovation, resilience, and sustainability in food production and distribution systems (*Biegler, L.T. et al, 1995)*.

In fig. 6 presents various applications and objectives of MOO in the food industry, focusing on essential objectives such as reducing operational costs, environmental sustainability, food quality and food safety *(Arteaga-Cabrera, E. et al, 2025).*

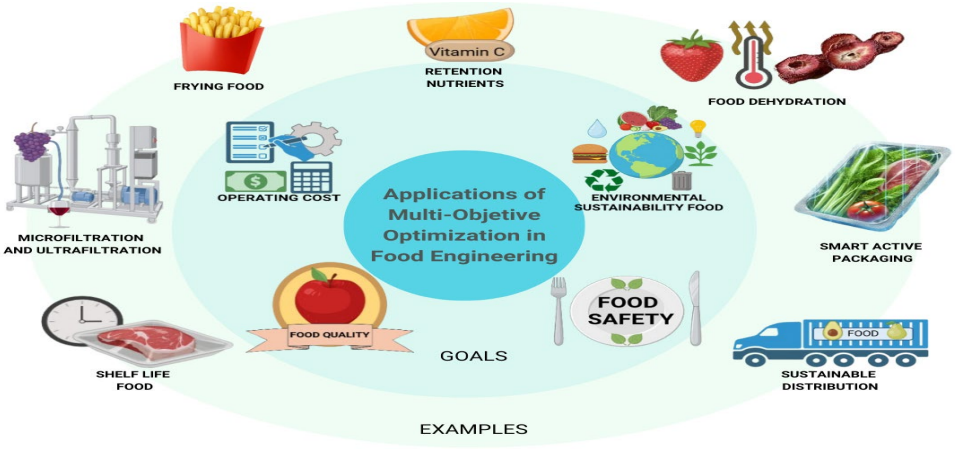

Fig. 6 - Applications of multi-objective optimization in food engineering.
(Arteaga-Cabrera, E. et al, 2025)

RESULTS

By using the information obtained from studying the specialized literature on multi-objective optimization, forecasting models and sensors used in agriculture, the focus was on the benefits and possible limitations of forecasting models and sensors. In Table 1, we have presented the smart devices on which the study of this paper was in-depth, where we presented the applications of each model and also their benefits and limitations in order to form a concise representation for the stakeholders.

Table 1

Benefits and limitations of forecasting models and sensors used in agriculture

Nr. crt.	Smart Agriculture		Instruments	Benefits	Limitation	Reference
1			Time series models (ARIMA and SARIMA)	informed decisions on resource allocation	sensitivity to non-stationary data	*Suresh,K.K.et al, 2011; Falatouri,T.et al, 2022*
				extension to processing programs	gestmanaging external variables	
2			Machine Learning (ML) Models (ML Models including RF and SVM)	solid information about market dynamics and resource optimization	Interpretability	*Kok,Z.H.et al, 2021; Suresh,N.et al, 2021*
					risk of overadaptation	
					computational requirements	
3		Forecasting models	Models DL (LSTM; CNN)	accurate predictions of impacts on the environment and agricultural systems	high computational cost	*Jaiswal,R.et al, 2022; Prashanthi,V. and Srinivas,K., 2020*
				monitors crop health and predicts supply disruptions	data requirements and difficulty in understanding outputs	
4			Time series + ML	accuracy of forecasts regarding yield and prices	for hybrid models there is no concrete data regarding their limitations	*Guo, Y., 2024; Özden,C., 2023*
5			ML+DL	effective in forecasting complex risks (pest outbreaks, extreme weather events)		*Paul,R.K. et al, 2022; Khatraty,Y. et al, 2022*
6			Clustering + ML	improved sales prediction in retail environments		*Udokwu,C.et al, 2022*
7	Sensors used in agriculture	Integrated equipment	Taidacent IP68 ABS Soil NPK Sensor, B08MXXSP59, Guangzhou, China	captures complete data on environmental and soil parameters (potassium, phosphorus, moisture, temperature and pH levels)	high costs: expensive for small or medium-sized farms	*Amazon, 2024; McCormick,A.,2017; Weraikat,D.et al, 2024*
					maintenance and calibration: sensors require periodic maintenance and calibration	
			Microcontrolerul ESP32 (SIMAC Electronics HANDEL GmbH, Neukirchen-Vluyn, Germania)		data security: data collection and transmission may raise security concerns	
					electromagnetic interference: from other devices	
					data interpretation: farmers must have the necessary knowledge and skills	

CONCLUSIONS

The benefits of forecasting models demonstrate their potential to play an instrumental role in addressing global food security challenges by increasing productivity, optimizing resource use, and reducing losses along the food supply chain. While there are limitations to forecasting models, particularly those related to data quality, model scalability, interpretability, and the infrastructure required for real-time forecasting, investing in technological innovation, fostering collaborations, and developing accessible and explainable tools that can be used successfully is essential. Forecasting models can become a vital component in building a sustainable, resilient, and productive global food system.

The benefits of sensors used in agriculture support the collection of accurate and real-time data, which helps farmers make data-driven decisions that optimize resource use, increase crop yields, and promote environmental sustainability. In the case of limitations, to minimize them, it is important to choose

reliable sensors and implement an appropriate maintenance and calibration strategy. It is also essential to ensure data security and provide farmers with training and support to use the technology effectively.

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EXTENSIVE GREEN ROOFS FOR SMART BUILDINGS
/
ACOPERIȘURI VERZI EXTENSIVE PENTRU CLADIRI SMART

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Keywords: green roof, Subsurface Textile Irrigation (SSTI), water reuse, water efficiency, agrivoltaics.

ABSTRACT
This paper presents a comparative evaluation of innovative irrigation technologies for extensive green roofs integrated into smart buildings. The study analyzes the Pirouz self-irrigated system and the Subsurface Textile Irrigation (SSTI) solution, focusing on water efficiency, moisture distribution, and structural performance. Simulation results show irrigation water savings of up to 70% and improved substrate uniformity compared to conventional systems. Both technologies allow the reuse of filtered greywater, supporting circular resource management. The findings confirm their potential to enhance building sustainability, reduce urban heat, and improve environmental resilience.

REZUMAT
Lucrarea prezintă o evaluare comparativă a tehnologiilor inovatoare de irigare pentru acoperișuri verzi extensive integrate în clădiri inteligente. Studiul analizează sistemul autoirigat Pirouz și soluția de irigare cu textile subterane (SSTI), având ca obiectiv eficiența apei, uniformitatea umidității și performanța structurală. Rezultatele simulărilor arată economii de apă de până la 70% și o distribuție mai uniformă a umidității comparativ cu sistemele convenționale. Ambele tehnologii permit reutilizarea apei gri filtrate, susținând economia circulară. Concluziile confirmă potențialul acestora de a îmbunătăți sustenabilitatea clădirilor și reziliența urbană.

INTRODUCTION
In recent decades, the rapid pace of urbanization and the growing demand for energy-efficient buildings have intensified interest in sustainable architectural solutions. Among these, *green roofs*—vegetated layers installed on the rooftops of buildings—represent one of the most effective nature-based strategies for mitigating urban environmental challenges. *Extensive green roofs*, in particular, are characterized by lightweight substrates (typically 5–15 cm thick), low-maintenance vegetation such as sedums and grasses, and adaptability to a wide range of structural systems. Unlike intensive systems, which function as accessible gardens, extensive green roofs prioritize environmental performance and scalability across large urban surfaces (*Antrop M., 2004; Beradi and Ghaffarian, 2019*).

Integrating extensive green roofs into *smart building* design aligns with contemporary concepts of digitalized and climate-adaptive architecture. These systems contribute to thermal insulation, reduction of the urban heat island effect, stormwater management, and enhancement of air quality, while simultaneously improving building energy performance. When equipped with sensor networks and IoT monitoring tools, green roofs become intelligent components capable of regulating irrigation, detecting substrate moisture, and transmitting real-time environmental data (*Lee et al., 2015; Shafique et al., 2018; Fioretti et al., 2010)*.

The implementation of such hybrid *eco-digital infrastructures* supports the transition toward sustainable cities and aligns with the European Green Deal objectives for climate-neutral buildings by 2050. This paper explores the functional characteristics, environmental benefits, and technological integration of extensive green roofs in the context of smart buildings, focusing on their potential to improve urban resilience, resource efficiency, and long-term sustainability (*European Union, 2015; Getter and Rowe, 2006*).

Systems for extensive green roofs that combine:

- a network of pipes for water storage,
- a innovative multi-chamber filters,

- a optimized drainage layer,
- a and the use of stored water for both irrigation and other domestic and civil uses.

Fig. 1 - Green systems for buildings
(https://www.permagard.co.uk/advice/green-roof-construction)

It also provides a comprehensive analysis of the system's performance compared to conventional green roofs – including water retention, runoff filtration, irrigation needs, etc (*Xu et al., 2012*).

Other relevant complementary technologies

• **Subsurface Textile Irrigation (SSTI)** – an underground system that distributes water and nutrients directly to the roots, reducing evaporation losses and allowing the use of recycled water: o it makes water consumption more efficient with savings between 50–75%; it has an exceptional lifespan; o it can cover large volumes of soil; it ensures uniform distribution through capillary geotextiles; o it is also adapted for commercial areas or urban green projects (*https://en.wikipedia.org/wiki/Subsurface_textile_irrigation*).

• **"Green roof + agrivoltaic" approaches** – plants grown under solar panels on the roof: o the shade created reduces evaporation by up to 50–66% and, by cooling the air, improves the efficiency of photovoltaic panels; o bi-functional system: food production + solar energy + reduction of the urban heat island effect (*https://www.wired.com/story/the-ultra-efficient-farm-of-the-future-is-in-the-sky*).

• **Rainwater and greywater reuse** – controlled use of collected water for rooftop irrigation: o approach through advanced models (MPC) that anticipate weather conditions and optimize pump control; o reduce drinking water consumption and dependence on the municipal network *(https://arxiv.org/abs/2110.13669).*

In Romania, green-roof adoption is still at an early stage; the European Federation of Green Roof Associations reports roughly **~400,000 m²** of green roofs nationwide, with no comprehensive national inventory yet in place, despite strong potential to mitigate urban heat and manage stormwater (*EFB, 2023; Berardi & Ghaffarian Hoseini, 2019*).

This paper presents an approach to green roof, taking into account the pressure on urban green spaces and the need for rooftop use, the challenges regarding water consumption, runoff management and plant efficiency, theoretical foundations, types of green roofs and principles of phytoremediation, retention, and thermoregulation.

MATERIALS AND METHOD

The systems studied in this paper integrate two innovative technologies for extensive green roofs: (i) the Pirouz self-irrigated system with multilayer filters and PVC reservoirs, and (ii) Subsurface Textile Irrigation (SSTI) for optimized water delivery at the root zone.

The modular platform consists of a waterproof membrane, root barrier, and lightweight vegetative substrate (5–15 cm depth). Below the substrate, PVC pipes (Ø 75–110 mm) form a storage and drainage network, allowing rainwater and greywater retention. Above these pipes, multi-chamber ceramic and polypropylene filters ensure sequential sediment capture and purification, enabling the reuse of treated water for irrigation. The SSTI layer—comprising subsurface drip lines covered by a capillary geotextile—distributes moisture laterally by capillarity, maintaining uniform soil humidity while minimizing evaporation losses (*Pirouz et al., 2023)*.

System performance was assessed through simulation and literature-validated parameters (*Pirouz et al., 2023; Sunnylands Foundation, 2017*). Comparative evaluation with conventional green roofs included parameters such as water consumption, moisture uniformity, structural weight, and suitability for integration with photovoltaic (agrivoltaic) modules.

Subsurface Textile Irrigation (SSTI)

Structure: at the base it has an impermeable layer, over which drip tubes and a capillary geotextile are placed, covered by a superficial impermeable layer to avoid water "tunneling" to the surface.

Distribution method: the geotextile captures and spreads water in a capillary manner over distances of up to 2m from the dripper, transforming an emission point into a dispersed source of water under the substrate.

Typical installation: 15–20cm under the substrate in urban applications; 30–50cm in agriculture.

Significant benefits:

- 50–75% reduction in water consumption compared to surface irrigation;
- Allows the use of recycled or treated water – it does not reach the surface;
- Uniform distribution, avoiding evaporation and weed infestation.

Basic components of SSTI systems:

1. Drip tubes – placed under the substrate, transport water.
2. Capillary geotextile – placed above the tubes, takes water and distributes it evenly laterally.
3. Upper waterproof layer – prevents water from evaporating upwards.
4. Lower waterproof layer – isolates the system from the soil or the underlying structure (e.g. roof).

Water drains from the tube into the geotextile → is distributed horizontally by capillarity and moistens the surrounding root zone, without reaching the surface.

Table 1

Advantages of the SSTI System [13, 14, 17]

Advantage	Details
Significant reduction of water losses	Evaporation is minimal (water does not reach the surface).
Uniform distribution	The capillary geotextile ensures constant moisture throughout the entire root zone.
Allows the use of greywater or recycled water	Water does not reach the soil surface, so it does not come into contact with people or animals.
Prevents weed growth	The soil surface remains dry — fewer seeds can germinate.
Long service life	Over 20 years under normal conditions (according to manufacturers such as Irrigation & Water Technologies Australia).
Ideal for green roofs and urban spaces	Easy to install and maintain.

SSTI can be used for:

- Green roofs;
- Living walls;
- Urban green spaces (permeable pavements, public gardens);
- Urban and precision agriculture;
- Sports fields and luxury lawns.

Table 2

Comparison between SSTI and classic irrigation [13, 14, 17, 19]

Characteristic	Conventional Irrigation	SSTI
Evaporation	High	Very low
Runoff losses	Frequent	Minimal
Surface moisture	Yes	No
Risk of fungal diseases	High (due to surface humidity)	Very low
Maintenance requirements	Moderate	Low
Water distribution	Variable	Uniform

The Pirouz self-irrigated system represents an innovative water-management solution designed specifically for extensive green roofs and arid or semi-arid environments. Its core principle is based on multi-layered water retention and capillary redistribution, allowing the roof substrate to remain moist without the need for frequent surface irrigation (*Pirouz et al., 2023*).

The system integrates PVC or polypropylene drainage pipes with perforations that act simultaneously as *water reservoirs and distribution channels*. Above these, a sequence of filtering layers—including coarse gravel, sand, and synthetic textiles—facilitates gradual capillary movement of water toward the root zone. This configuration ensures efficient moisture balance, while preventing waterlogging or nutrient leaching.

A major innovation lies in the self-regulating drainage mechanism, which allows excess rainfall to be stored temporarily and reused during dry periods. The filtration unit removes sediment and organic debris, maintaining water quality suitable for plant uptake and permitting the safe use of recycled or greywater sources. The modular construction makes it adaptable to a variety of roof geometries and structural load limits.

Overall, the Pirouz system enhances hydrological efficiency, reducing irrigation needs by up to 60–70%, improving substrate moisture uniformity, and contributing to the long-term sustainability of vegetated roofs. When combined with digital monitoring tools, it forms an intelligent irrigation platform that supports energy-efficient, climate-resilient urban design.

Table 3

Advantages of the Pirouz Self-Irrigated System (*Pirouz et al., 2023, 20, 15*)

Advantage	Details
Water-saving performance	The multilayer reservoir and capillary redistribution reduce irrigation demand by up to 60–70% compared with conventional green roof systems.
Self-regulating drainage	Automatically retains excess rainwater in PVC reservoirs and gradually redistributes it to the substrate during dry periods.
Improved moisture uniformity	Maintains consistent humidity throughout the root zone, preventing localized drought or oversaturation.
Compatibility with recycled water	Integrated filtering layers allow the safe use of greywater and rainwater, reducing potable water consumption.
Lightweight modular design	Suitable for extensive green roofs due to low structural load and easy installation on flat or slightly sloped roofs.
Reduced maintenance requirements	Filters and reservoirs function autonomously for long periods, requiring minimal servicing.
Extended plant vitality	Stable water availability supports healthy root development and increased vegetation coverage.
Environmental sustainability	Enhances stormwater management, mitigates the urban heat island effect, and supports circular resource use.

The data presented in Table 3 highlight the multifunctional nature of the Pirouz self-irrigated system, which integrates water retention, filtration, and capillary redistribution into a compact modular design. By maintaining optimal substrate humidity and recycling stored rainwater, the system reduces irrigation demand and supports sustainable vegetation growth even under limited water availability. Its lightweight and low-maintenance structure make it particularly suitable for extensive green roofs, while the capacity to utilize greywater enhances environmental performance and aligns with circular resource management principles.

RESULTS AND DISCUSSIONS

Simulation data and previous studies confirm that the proposed system significantly improves hydrological efficiency. Annual irrigation demand decreased by up to **66%** compared with conventional drip systems, while moisture distribution remained uniform throughout the substrate profile. The integrated PVC reservoirs retained 30–70 L/m²/year, depending on pipe diameter, ensuring self-sufficiency during moderate drought periods.

The SSTI layer contributed to 50–75% reductions in evaporation losses, and by isolating water flow from the surface, allowed safe reuse of greywater. When coupled with photovoltaic modules, the system

demonstrated an additional 30–60% decrease in evaporation due to shading and a 4% increase in PV efficiency, confirming the advantages of agrivoltaic integration.

Overall, the combined system maintaines a lightweight structural profile, facilitated installation even on sloped roofs, and provided water treatment through replaceable multi-layer filters. Estimated savings for a 500 m² roof in a temperate-continental climate reached up to 50 m³ of potable water per year.

Table 4

Comparative Table of System Performance [16, 19]

Characteristic	Conventional Green Roof	Pirouz System (Self-Irrigated)	SSTI System
Water retention/storage (volume)	Limited (gravel + substrate)	High (in PVC tubes)	Geotextile + drip system
Irrigation need during dry periods	High	Low (subsurface automatic irrigation)	Very low
Evaporation losses	High	Minimal	Very minimal
Possibility of using recycled water	No	Yes (filtered and treated water)	Yes (does not reach surface)
Moisture uniformity	Variable	Controlled	Excellent
Structural weight	High (gravel + substrate)	Lower (tubes vs. gravel)	Depends on SSTI structure
Integration with PV systems	Without significant benefits	Yes (reduced evaporation and energy synergy)	Depends on integration level

The comparative analysis presented in Table 4 illustrates the operational and functional differences among conventional green roofs, the Pirouz self-irrigated system, and the SSTI subsurface irrigation technology. The Pirouz system demonstrates superior water-retention capacity through the use of PVC reservoirs, ensuring gradual moisture release and significantly lower irrigation requirements. Similarly, the SSTI configuration provides exceptional uniformity of moisture distribution and minimizes evaporation losses due to its capillary geotextile layer. Both advanced systems enable the safe reuse of recycled or treated greywater, contributing to resource efficiency and sustainability. In contrast, traditional green roofs rely on surface irrigation, which increases water consumption and structural weight while offering limited control over moisture dynamics. Overall, the integration of self-irrigated and subsurface systems represents a major step toward high-efficiency, low-maintenance solutions for urban green infrastructure and smart building applications.

Table 5

Simulation Examples with Comparative Real Water Consumption Values (liters/m²/year)

Characteristic	Conventional Green Roof	Pirouz System (Self-Irrigated)	SSTI System
Water retention/storage (volume)	Limited (gravel + substrate)	High (in PVC tubes)	Geotextile + drip system
Irrigation need during dry periods	High	Low (automatic subsurface irrigation)	Very low
Evaporation losses	High	Minimal	Very minimal
Possibility of using recycled water	No	Yes (treated through filters)	Yes (does not reach surface)
Moisture uniformity	Variable	Controlled	Excellent
Structural weight	High (gravel + substrate)	Lower (tubes vs. gravel)	Depends on SSTI structure
Integration with PV systems	Without multiple benefits	Yes (reduces evaporation + increases energy efficiency)	Depends on integration level

The comparative simulation results summarized in Table X clearly demonstrate the superior hydrological performance of the Pirouz and SSTI systems compared to conventional green roof configurations. Both innovative solutions substantially reduce water losses through evaporation and runoff, while maintaining consistent substrate moisture even under dry climatic conditions. The Pirouz self-irrigated system achieves this by storing water within PVC reservoirs and delivering it gradually through a capillary process, whereas the SSTI design ensures uniform distribution via geotextile layers and subsurface drip

lines. Additionally, both systems enable the reuse of treated greywater, lowering the demand for potable water. These findings underline the potential of smart irrigation technologies to enhance the efficiency, sustainability, and adaptability of urban green infrastructure.

CONCLUSIONS

The combined Pirouz + SSTI system represents a scalable, efficient solution for sustainable green roof irrigation. Its modular architecture supports rainwater retention, filtration, and reuse within a self-regulated cycle that drastically lowers potable water demand. Results highlight the potential of integrating smart control and renewable energy components to further enhance system autonomy.

By combining physical water management with digital monitoring, extensive green roofs can evolve into *eco-intelligent* infrastructure units that contribute to climate-resilient cities. Future research should focus on long-term pilot studies, AI-driven irrigation control, and standardization of lightweight materials for large-scale deployment.

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COMPARATIVE STUDY ON SOIL TYPES AND AGRICULTURAL POTENTIAL IN THE MAIN REGIONS OF ROMANIA

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STUDIU COMPARATIV ASUPRA TIPURILOR DE SOL ȘI POTENȚIALULUI AGRICOL ÎN PRINCIPALELE REGIUNI ALE ROMÂNIEI

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Keywords: *soil type; soil parameters; agricultural potential, fertility indicators, pedological diversity, sustainable land management.*

ABSTRACT

This paper presents a comparative assessment of the main soil types characteristic of three major agricultural regions of Romania: South-West Oltenia, South Muntenia, and North-East Moldova. The study integrates data from regional soil reports and typological classifications to evaluate pedological traits, fertility indicators, and agricultural suitability. The analysis reveals a clear spatial differentiation of soil quality and productive potential. Chernozems and Phaeozems exhibit high natural fertility and structural stability, supporting intensive cereal and industrial crop systems. Luvisols and Cambisols show moderate productivity constrained by acidity, compaction, and erosion, while Fluvisols provide favorable conditions for irrigated vegetable and forage crops. In contrast, Arenosols and Regosols are limited by coarse texture and low humus content, suitable mainly for drought-tolerant or perennial crops. The results emphasize the importance of region-specific soil management practices, including liming, organic amendments, and irrigation, to maintain fertility and ensure sustainable agricultural performance in line with European soil health and climate adaptation strategies.

REZUMAT

Lucrarea prezintă o evaluare comparativă a principalelor tipuri de sol specifice celor trei mari regiuni agricole ale României: Sud-Vest Oltenia, Sud Muntenia și Nord-Est Moldova. Studiul integrează date din rapoarte regionale de sol și clasificări pedologice pentru a analiza caracteristicile tipologice, indicatorii de fertilitate și gradul de favorabilitate agricolă. Analiza evidențiază o diferențiere spațială clară a calității solului și a potențialului productiv. Cernoziomurile și faeoziomurile prezintă o fertilitate naturală ridicată și o structură stabilă, susținând sisteme agricole intensive pentru cereale și culturi industriale. Luvisolurile și cambisolurile înregistrează o productivitate moderată, limitată de aciditate, compactare și procese de eroziune, în timp ce fluvisolurile oferă condiții favorabile pentru legume și culturi furajere în sistem irigat. În contrast, arenosolurile și regosolurile, caracterizate prin textură grosieră și conținut redus de humus, sunt potrivite doar pentru culturi perene sau tolerante la secetă. Rezultatele subliniază necesitatea aplicării unor practici de gestionare adaptate condițiilor regionale – amendamente calcaroase, fertilizare organică și irigații – pentru menținerea fertilității și asigurarea unei agriculturi durabile, în concordanță cu obiectivele europene privind sănătatea solului și adaptarea la schimbările climatice

INTRODUCTION

Soil resources represent one of the most important components of Romania's natural capital, underpinning agricultural production, ecosystem services, and rural development. The country's pedological diversity reflects the combined influence of climatic gradients, relief variability, and lithological heterogeneity, leading to the formation of highly productive Chernozems, moderately fertile Cambisols, and more constrained Luvisols and Podzols. Understanding this spatial variability is crucial for optimizing land use and ensuring sustainable crop production (*ICPA, 2012; MADR, 2024*).

Romania's agricultural regions—South-West Oltenia, South-Muntenia, and North-East Moldova—offer representative examples of soil heterogeneity, ranging from drought-prone sandy soils in Oltenia to erosion-sensitive Luvisols in Moldova. Such diversity affects both yield potential and the types of crops best

suited for cultivation. The adaptation of soil management practices to local characteristics, including fertilization, irrigation, and conservation measures, is therefore a key factor in achieving productivity and environmental sustainability (*Bucur et al., 2007*; *European Commission, 2022*).

To illustrate the complex interdependence between soil characteristics and agricultural performance, an integrative conceptual model was developed (Figure 1). This infographic summarizes the main physical, chemical, and biological properties that determine soil quality and how these influence key agricultural outcomes. By linking fundamental soil parameters—such as texture, organic matter, and nutrient balance—to yield potential and resource efficiency, the model emphasizes the functional role of soil as a living system underpinning sustainable crop production.

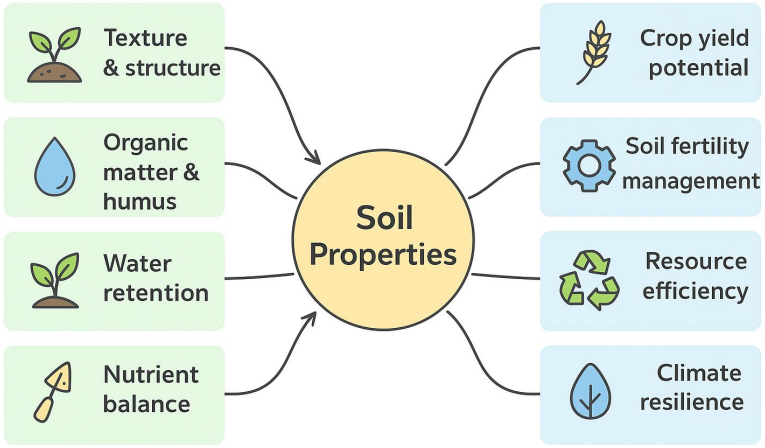

Fig. 1 - Main properties of soils in relation with agricultural potential

As shown in Figure 1, soil properties act as the foundation of agricultural potential. Well-structured soils with adequate organic matter and balanced nutrient content promote effective water retention, root development, and microbial activity, which in turn enhance crop productivity and long-term fertility. Conversely, degradation of any of these properties—through erosion, compaction, or nutrient imbalance—reduces efficiency and resilience. The diagram therefore highlights how maintaining soil health directly supports climate adaptation, resource sustainability, and overall farm performance in agricultural systems.

This study aims to compare the main soil types and their agricultural potential across these regions, identify limiting factors, and propose regionalized management strategies to support sustainable intensification and compliance with CAP 2023–2027 priorities related to soil health and climate adaptation.

MATERIALS AND METHODS

The analysis was conducted using data extracted from regional soil studies for Oltenia, Muntenia, and Moldova (2023–2024), as well as national pedological classifications (*ICPA database*). Parameters considered included soil type distribution, humus content, texture class, reaction (pH), base saturation, available water capacity (AWC), and known limiting factors (erosion, salinity, compactness). The evaluation focused on correlating these characteristics with the main agricultural crops cultivated in each region and their productivity potential.

The South-West Oltenia region is characterized by a predominance of Chernozems, Cambisols, and Arenosols, reflecting a gradual transition from fertile plains to more eroded upland terrains. The Calcaric and Cernic Chernozems found on the terraces of the Danube and Jiu Rivers represent some of Romania's most productive soils, with high humus content (3–5%), balanced structure, and excellent nutrient availability. These soils sustain intensive cultivation of maize, wheat, sunflower, and sorghum, although their fertility is threatened by drought and low water-holding capacity. In contrast, the sandy formations around Dăbuleni and Bechet are dominated by Arenosols and Regosols, where coarse texture, weak aggregation, and rapid drainage create severe moisture deficits during summer. Here, sustainable use depends on irrigation, mulching, and the introduction of drought-tolerant crops. On the piedmont slopes, Eutric Cambisols and Luvisols with medium fertility are present, supporting orchards, vineyards, and pastures when erosion control measures are applied (*Dumitru et al., 2011*).

The soils of the South-Muntenia region display significant variability influenced by relief, parent material, and climatic gradients. The most widespread are Luvisols, Cambisols, and Phaeozems, associated

with the vast plains of Teleorman, Argeș, and Ialomița counties. Luvic soils, often slightly acidic (pH 5.5–6.2), exhibit clay illuviation in the Bt horizon and moderate fertility, suitable for cereals, oilseed rape, and vineyards when properly limed and fertilized. Cambisols predominate in hilly areas and terraces, offering balanced physical properties but showing moderate erosion susceptibility. Phaeozems occur locally in depressions and areas with higher organic matter accumulation, supporting maize, sunflower, and forage crops. Despite favorable climatic conditions, the main limiting factors are periodic droughts, structural compaction, and erosion on slopes, which require conservation tillage, contour farming, and organic amendment practices to preserve productivity and soil structure (*Vintila et al., 2004; Vlad et al., 2010*).

The North-East region of Moldova presents one of Romania's most diverse and complex pedological landscapes, dominated by Luvisols, Chernozems, and Regosols formed under the influence of hilly relief, loessic deposits, and continental climate. Luvisols are the most extensive, especially on the Central Moldavian Plateau, where strong textural differentiation, moderate acidity, and erosion susceptibility limit intensive agriculture. However, with proper fertilization and liming, they can sustain profitable wheat, barley, and sunflower crops. Chernozems occur in the Botoșani–Iași area and remain highly fertile, with humus content above 4% and excellent structure, ideal for cereals and sugar beet cultivation. On steep slopes and recently eroded surfaces, Regosols and Erodosols are common, showing poor horizon development and requiring reforestation or perennial grass establishment to reduce land degradation. Overall, the agricultural potential of Moldova remains significant, provided that erosion control, organic matter restoration, and adaptive crop rotations are implemented (*Patriche et al., 2024; Matei et al., 2020; Niacsu et al., 2015*).

A comparative matrix was developed to highlight similarities and differences between regions. Oltenia's soils were characterized by the prevalence of Chernozems and Arenosols with good fertility but moderate water retention; Muntenia displayed a predominance of Luvisols and Cambisols with variable pH and structural instability; Moldova showed a complex pattern dominated by Luvisols and Chernozems, strongly affected by erosion and slope gradients.

The comparative analysis used qualitative and semi-quantitative indicators to assess soil fertility and potential agricultural use, supported by literature and field data from the Ministry of Agriculture and the National Research-Development Institute for Soil Science (ICPA, 2022).

RESULTS

Soil distribution and regional characteristics

- **South-West (S-W) Oltenia:** Soils are dominated by Chernozems and Cambisols, with moderate to high fertility and good nutrient balance. Arenosols appear in the southern sandy areas (Dăbuleni), where low water-holding capacity and drought risk limit crop productivity. Suitable crops include maize, sunflower, and sorghum, with irrigation required for stability.
- **South (S) Muntenia:** Luvisols and Phaeozems predominate, moderately acidic and rich in clay, favoring cereals, rapeseed, and vineyards. Soil compaction and reduced aeration are local constraints. Cambisols on slopes support orchards and pastures but require erosion control.
- **North-East (N-E) Moldova:** The region has a mosaic of Luvisols, Chernozems, and Regosols. Erosion is the main degradation factor due to the hilly relief. Despite good natural fertility, yield variability is high. Cereals (wheat, barley) and industrial crops (sugar beet, sunflower) are dominant.

The comparative synthesis presented in Table 1 highlights the pedological and agronomic diversity of the analyzed regions.

Table 1

Technological traits of the main soil types in the regions studied

Region	Dominant soil types	Fertility level	Main limiting factors	Recommended crops
South-West Oltenia	Chernozems, Cambisols, Arenosols	Medium–high	Drought, low water capacity	Maize, sunflower, sorghum
South Muntenia	Luvisols, Cambisols, Phaeozems	Medium	Acidity, compaction, erosion	Wheat, barley, rapeseed, vineyards
East Moldova	Luvisols, Chernozems, Regosols	Medium–high	Erosion, acidity, slope	Wheat, barley, sugar beet, sunflower

South-West Oltenia is characterized mainly by highly fertile Chernozems and Cambisols, whose productivity is occasionally limited by drought and low water-holding capacity. In South Muntenia, Luvisols and Cambisols dominate, displaying moderate fertility but structural and acidity constraints that necessitate corrective practices such as liming and organic fertilization. East Moldova mainly exhibits a mixture of Luvisols, Chernozems, and Regosols, where erosion and slope conditions reduce yield stability despite relatively high inherent fertility. The recommended crop systems reflect these constraints, emphasizing cereals and industrial crops in fertile plains, and forage or vineyard crops on more fragile terrains.

To provide a comprehensive understanding of the pedological diversity that shapes Romania's agricultural productivity, Table 2 summarizes the main physical, chemical, and biological parameters of the dominant soil types identified in the analyzed regions (Oltenia, Muntenia, and Moldova). The comparative data highlights the contrasting fertility levels, structural properties, and water retention capacities that determine the suitability of each soil for specific crops and management practices. These indicators represent averaged values derived from regional soil surveys and typological classifications established according to the Romanian Soil Taxonomy System (*Tarau et al., 2012*).

Table 2

Parameters and characteristics of soil types in S-W Oltenia, S – Muntenia and N-E – Moldova Regions

Parameter	Soil type						
	Chernozems	**Luvisols**	**Cambisols**	**Phaeozems**	**Fluvisols**	**Arenosols**	**Regosols**
Texture	Loam–loam-clay; stable granular structure	Loam–clay loam (Ap/E); clayey Bt (argic)	Clay loam to clay; weathering horizon	Loam; intermediate between Chernozems & Luvisols	Sandy loam to loam; stratified alluvium	Fine sand to fine sandy loam; >70% sand	Sandy loam/loamy sand; weak profile
pH	6.8–7.8 (neutral–slightly alkaline)	5.2–6.8 (slightly acidic–neutral)	5.8–6.8 (slightly acidic–neutral)	6.3–7.2 (near neutral)	6.5–7.8 (neutral–slightly alkaline)	5.0–6.2 (acidic to slightly acidic)	5.5–6.8 (slightly acidic–neutral)
Humus content (%)	3.5–5.5	1.8–3.0	2.0–3.2	3.0–4.0	1.8–3.5	0.6–1.5 (very low)	1.0–2.5 (low)
Base saturation (V%)	85–100 (high)	50–75 (moderate)	65–85 (well base-saturated)	70–90 (high)	>75 (often >85)	35–55 (low–moderate)	40–60 (low–moderate)
Water-holding capacity (AWC, %)	12–14	10–12	12–15	11–14	12–17	5–9	8–14
Bulk density (g/cm³)	1.20–1.35	1.35–1.50 (higher in Bt)	1.30–1.45	1.25–1.40	1.30–1.45	1.40–1.65	1.40–1.60
Total porosity (%)	48–55	38–45 (lower in Bt)	48–53	~50	45–52	35–42	—
Biological activity	High (active microbiota, mull humus)	Medium (limited in Bt)	Medium–high	High (humus-rich)	Medium–high	Low	Low–medium
Color & morphology	Dark; deeper; stable structure	Yellowish-brown; reddish with clay coatings	Dark brown; light to reddish	Dark surface horizon; leached subsurface	Stratified alluvial layers; weak profile	Light-colored sands; weak structure	Light brown to grayish; Thin; weakly developed

As shown in Table 2, Chernozems exhibit the highest fertility, reflected by their balanced structure, neutral to slightly alkaline pH, and high humus content, making them ideal for cereal and industrial crops. Luvisols and Cambisols show moderate productivity, constrained by acidity and higher bulk density in the Bt horizon, while Phaeozems represent a transitional type with favourable humus levels and improved structure. Fluvisols display good agricultural potential under irrigation, whereas Arenosols and Regosols are limited by coarse texture, low nutrient reserves, and reduced water-holding capacity. The overall comparison underscores the need for region-specific soil management, including liming, organic amendments, and irrigation, to sustain productivity and prevent degradation.

Figure 2 summarizes the relative compatibility of dominant soil groups with representative crop categories, based on regional soil characteristics described in the S-W Oltenia, S - Muntenia, and N-E - Moldova profiles. Suitability levels (High, Moderate, Low) were established considering each soil's texture, nutrient status, water-holding capacity, and limiting factors (acidity, erosion, salinity, drought susceptibility).

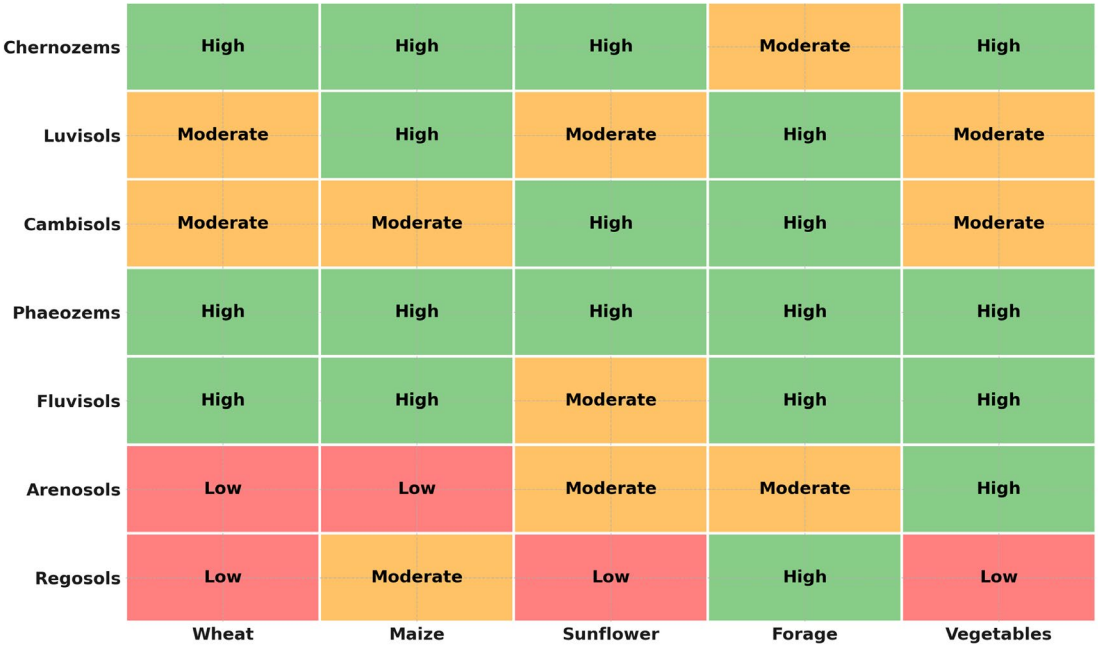

Fig. 2 - Agricultural suitability matrix of main soil types in Romania

Figure 3 presents the relative importance of major soil types in the regions studied, emphasizing their agricultural potential and limitations.

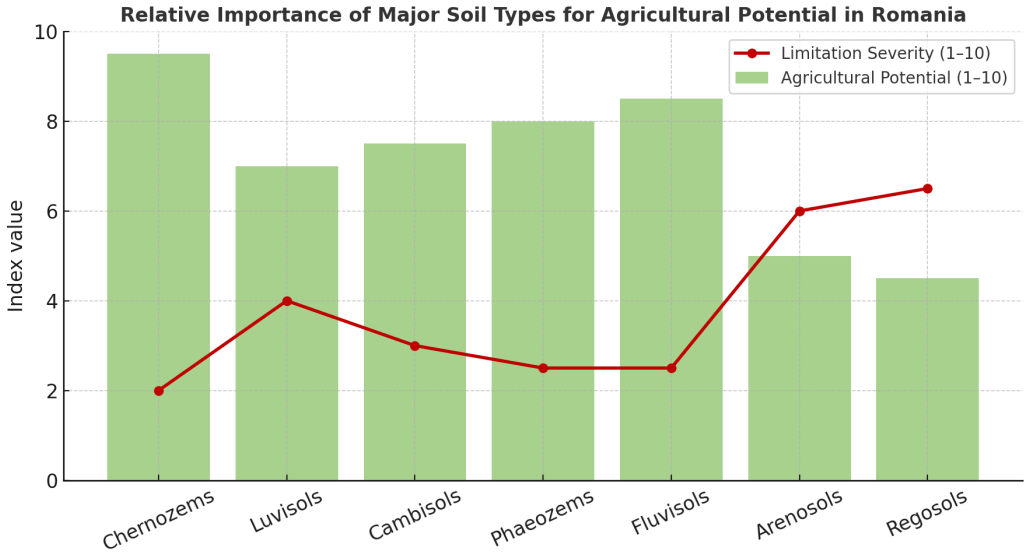

Fig. 3 - Relative importance of major soil types for Agricultural potential in Romania

As it can be observed from Figure 3, Chernozems stand out as the most fertile soils, with the highest potential index and minimal limitations, supporting intensive cereal and industrial crop systems. Luvisols and Cambisols show moderate potential, constrained by acidity and structural issues, while Phaeozems and Fluvisols maintain relatively high productivity under appropriate management. In contrast, Arenosols and Regosols display reduced agricultural value due to poor texture, low water-holding capacity, and erosion susceptibility. Overall, the figure highlights the clear gradient between fertile, structurally balanced soils and those requiring careful conservation and amelioration to sustain productivity.

CONCLUSIONS

The comparative evaluation of soil types in South-West Oltenia, South Muntenia, and East Moldova highlights the strong pedological variability that underpins Romania's agricultural potential. Chernozems and Phaeozems exhibit the highest fertility, with balanced structure, neutral pH, and high humus content, supporting intensive cereal and industrial crop systems. In contrast, Luvisols and Cambisols show moderate productivity, constrained by acidity, compaction, and erosion risks, yet remain valuable under integrated management practices involving liming, organic amendments, and conservation tillage. Arenosols and Regosols represent fragile soil resources, characterized by coarse texture, weak aggregation, and low water retention, limiting their suitability mainly to drought-tolerant or forage crops under irrigation.

Regional patterns confirm that soil fertility and management constraints are closely linked to climatic and geomorphological conditions. Oltenia's productivity is mainly affected by drought, Muntenia by acidity and compaction, and Moldova by erosion and slope gradients. These findings emphasize the necessity of tailored soil conservation and fertility improvement strategies that align with local characteristics and European soil health objectives under the CAP 2023–2027 framework.

Overall, the study demonstrates that sustainable agricultural performance in Romania depends on maintaining soil structure, enhancing organic matter content, and implementing adaptive land management practices. Strengthening monitoring programs and integrating digital mapping tools (e.g., SIGSTAR, BDUST) will be essential for optimizing land use and safeguarding soil resources as part of the national and European agenda for climate-resilient agriculture.

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MINERAL COMPOSITION AND AROMA QUALITY IN BAY LAUREL *(LAURUS NOBILIS)* LEAVES / *COMPOZIȚIA MINERALĂ ȘI CALITATEA AROMEI FRUNZELOR DE DAFIN (LAURUS NOBILIS)*

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Keywords: *nutritional profile, XRF analysis, sensory observations, plant adaptability*.

ABSTRACT

Bay laurel (Laurus nobilis) is a Mediterranean evergreen plant generally valued for its culinary and medicinal uses. The aim of this study was to evaluate the mineral composition of bay leaves cultivated in Dumbravita, Timis County, Romania, using portable X-ray fluorescence (XRF). Two sets of samples (fresh and dry leaves) were analyzed and compared. Understanding the mineral profile is essential for assessing quality, safety, and plant adaptation to diverse environments. The results established the adaptability of Laurus nobilis to Romanian climatic conditions. In addition to mineral characterization, sensory observations showed that local bay leaves display a spicy and intense aroma, noticeably stronger than that of commercial products. These conclusions suggest that environmental conditions and mineral uptake may influence both the nutritional profile and sensory quality of bay laurel, supporting its potential as a functional and gastronomic resource.

REZUMAT

Dafinul (Laurus nobilis) este o plantă mediteraneană veșnic verde, apreciată în general pentru utilizările sale culinare și medicinale. Scopul acestui studiu a fost de a evalua compoziția minerală a frunzelor de dafin cultivate în Dumbrăvița, județul Timiș, România, cu ajutorul spectrometrului cu fluorescență de raze X (XRF). Au fost analizate și comparate două seturi de probe (frunze proaspete și uscate). Înțelegerea profilului mineral este esențială pentru evaluarea calității, siguranței și adaptării plantelor la diverse medii. Rezultatele au stabilit adaptabilitatea speciei Laurus nobilis la condițiile climatice românești. Pe lângă caracterizarea mineralelor, observațiile senzoriale au arătat că frunzele de dafin locale prezintă o aromă picantă și intensă, vizibil mai puternică decât cea a produselor comerciale. Aceste concluzii sugerează că condițiile de mediu și absorbția mineralelor pot influența atât profilul nutrițional, cât și calitatea senzorială a dafinului, susținând potențialul său ca resursă funcțională și gastronomică.

INTRODUCTION

Laurus nobilis L. (Lauraceae), generally known as bay are shrubs or small trees (*https://greenwoodplants.co.uk/blog/plant-focus-laurus-nobilis-bay-laurel/*), is native to the southern Mediterranean region, commonly cultivated in Europe and the USA as an ornamental plant and as aromatic leaves in countries like Turkey, Algeria, Morocco, Portugal etc. (*Awada, F. at al, 2023, Guenane, H. at al, 2016)*. The bay laurel is unisexual, with male and female flowers on separate plants (https://www.treeguideuk.co.uk/bay-tree-identification/).

All over the world, there is increasing awareness in the importance of dietary minerals in nutrition and for the prevention of several diseases [6]. Although minerals justify for only a small percentage of plant biomass, they are vital for the sensory and nutritional properties of e bay laurel (Laurus nobilis) leaves. The minerals in bay leaves are macro elements like calcium, potassium, magnesium, phosphorus (*Al-Hashimi, A. G. at al, 2016*) and trace elements (iron, zinc, copper, iodine, chromium, manganese, etc.), each serving various scientific and biological objectives.

In Laurus nobilis, potassium and calcium lead the mineral spectrum, regulating osmotic balance in the plant, stabilizing cell walls, and shaping the resilience of leaves under Mediterranean and continental climates

(*Ishimwe, C at al, 2024*). These same minerals, when consumed, contribute to electrolyte balance, skeletal health, and cardiovascular protection in humans. Leading the mineral spectrum in bay plant, potassium and calcium control osmotic balance in the plant, stabilize cell walls, and shape the resilience of leaves under Mediterranean and continental temperatures. Consumed, these same minerals assist people in preserving their cardiovascular health, skeletal structure, and electrolyte balance (*Hasanuzzaman, M. at al, 2018*).

The trace minerals (iron, zinc, copper, and manganese), present in smaller amounts, act as cofactors for enzymatic systems responsible for photosynthesis, respiration, and phenolic biosynthesis, which in turn influence antioxidant potential and aroma compounds (*Trairatapiwan, T. at a, 2025*).

While trace metals like zinc and iron interact with secondary metabolites, influencing the spicy, resinous, and persistent taste, potassium and magnesium manage volatile oil metabolism, a scent that elevates their culinary worth.

The minerals present in bay plant leaves reveal the soil and ecological environment where the tree is grown as well as explains the leaves odor, a stronger smell when set against those commercially brought in. Therefore, bay laurel shows how minerals, however numerically small, are qualitatively critical. Supporting the plant structurally and physically, they improve the nutritional profile of human diets and interact with phytochemicals to provide both health advantages. gastronomic perfection as well as (anti-inflammatory action, digestive stimulation, antioxidant protection).

MATERIALS AND METHODS

Plant material

Bay laurel (Laurus nobilis) leaves were collected from cultivated plants in Dumbravita, Timis County, Romania. We worked with two types of material: dried leaves (1F), obtained by oven-drying at 60 °C until constant weight, and fresh leaves (2F), analyzed immediately after harvesting (*Nica, D. at al, 2012*). To make the results analogous, concentrations from both sets of samples were expressed on a dry weight basis (*Şuian, B. at al,2025*). Before analysis, leaves were carefully rinsed with distilled water. Dried leaves were finely ground and pressed into stable pellets, while fresh leaves were compacted into discs of the similar size to confirm comparable conditions during measurement.

XRF analysis

Elemental composition was determined using a portable X-ray fluorescence spectrometer (Hitachi X-MET8000). Each sample type (1F and 2F) was analyzed in triplicate (*Tarkanyi, P. at al, 2024*).

The pellets and discs were prepared with a manual press to offer a uniform surface, improving precision. The instrument was operated in its soil/plant mode, which is optimized for detecting both major nutrients and trace metals. To bring the results closer to reference laboratory methods such as ICP-AES, we applied element-specific correction factors based on previous work with plant matrices (e.g. K and Ca: 0.8, Fe/Zn/Cu: 0.6, Ni: 0.5, Ti/Mo: 0.2, Ba/Sr: 0.3). All results are presented in ppm (mgkg-1 DW).

Detection limits

The sensitivity of the XRF allowed us to detect trace metals down to ~1–5 ppm (e.g. Cd, Pb, Hg, As), 5–10 ppm for transition metals such as Fe, Cu, and Zn, and around 50–100 ppm for abundant elements like K and Ca. Measurements below the detection limit were reported as “not detected” (ND). Elements close to the quantification limit (roughly three times the LOD) were double-checked through repeated analysis.

Literature data

For comparison, we used published values from ICP-AES and WD-XRF (Sultana S. at al, *2023*) studies of Moroccan bay leaves (*Mrabet et al., 2024*), AAS analyses of Algerian samples (*Guenane et al., 2016*), and compositional values reported in the Foodstruct nutritional database (*https://foodstruct.com/food/bay-leaf*).

Data handling

We compiled our results and literature values into a single comparative dataset. The interpretation of data was made using PAST version 2.17c (*Hammer, O. at al, 2001*) and Microsoft Excel. These tools helped us highlight where local Romanian samples stood out against previously published data.

RESULTS

Our XRF measurements showed that bay laurel leaves grown in Dumbravita, Timis County accumulate a rich and diverse set of minerals, but with some clear differences compared to values reported in the literature. Because we analyzed both dried leaves (1F) and fresh leaves (2F), all results are expressed on a dry weight basis so they can be compared directly (Table 1).

Table 1

Mineral composition of dry and fresh bay leaves (mgkg^{-1})

Element	LAB1F	LAB2F	LIT-ICP-AES [6]	LIT-WD-XRF	LIT-Foodstruct [8]
K	19152	18046.4	4646	6340	5290
Ca	26325.6	18249.6	10013	9730	8340
Fe	258	277.8	124	427	430
Cu	21.96	18.36	3.48	24	4.2
Mn	320	250	72	170	82
Mo	0.28	0.32		-	-
Zn	57.24	45.36		56	37
Ni	ND	5		240	
Ti	1.64	7.88		-	
Ba	12.15	13.5		-	
Zr	0.12	ND		-	
Sr	2.7	1.53		510	
Rb	1.76	1.6			
Cr	7	ND			
Ta	19	26			
Sb	13	21			
Hg	0.13	0.12			
Cd	ND	ND			
Tl	ND	ND			

Legend: LAB1F= dried bay leaves analyzed in our laboratory using XRF; LAB2F= fresh bay leaves analyzed in our laboratory using XRF; LIT-ICP-AES = literature data – minerals detected by ICP-AES, LIT-WD-XRF= literature data – minerals detected by WD-XRF; LIT-Foodstruct = minerals data of bay leaves from Foodstruct.com

As we can observe in Table 1 and Figure 1, potassium (K) and calcium (Ca) were the most abundant elements in our samples, much higher than those typically reported from Morocco or Algeria. This suggests that bay laurel grown under Romanian conditions has a superior capacity to take up and store these elements, possibly because of the soil composition, or climate. Higher K and Ca levels may also contribute to the strong, spicy aroma that local users notice related to imported bay leaves.

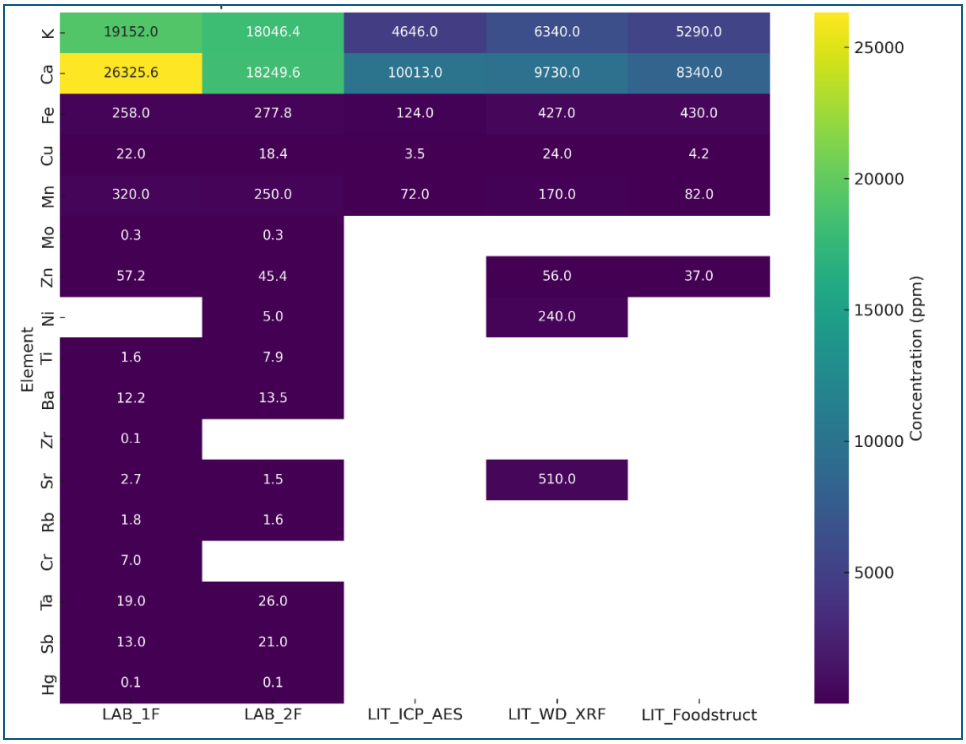

Fig. 1 - Heatmap of LAB versus Literature data for Laurus nobilis leaves

Legend: LAB1F= dried bay leaves analyzed in our laboratory using XRF; LAB2F= fresh bay leaves analyzed in our laboratory using XRF; LIT-ICP-AES = literature data – minerals detected by ICP-AES, LIT-WD-XRF= literature data – minerals detected by WD-XRF; LIT-Foodstruct = minerals data of bay leaves from Foodstruct.com

The laboratory results for the transition elements Fe and Zn were in line with food database data (~430 ppm) and WD-XRF measurements, but higher than some ICP-AES values (124 ppm). Manganese (Mn), however, stood out: our samples contained 250–320 ppm, while literature values rarely exceeded 170 ppm. This suggests a strong local enrichment of Mn, possibly linked to the soil parent material or higher bioavailability.

Regarding trace and minor elements, we also found elements such as nickel (Ni, ~5 ppm), chromium (Cr, ~7 ppm), strontium (Sr, 1–3 ppm), barium (Ba, 12–14 ppm), rubidium (Rb, 1–2 ppm), and titanium (Ti, 1–8 ppm). These were either absent or rarely reported in the literature. In addition, we detected small amounts of antimony (Sb, 13–21 ppm) and mercury (Hg, 0.12–0.13 ppm). While very low, these findings are important because such elements are seldom measured in bay leaves. Their presence likely reflects natural soil background rather than contamination, but they highlight the usefulness of XRF for broad-spectrum screening.

From the toxicological point of view, elements of major concern such as cadmium, lead, thallium, and arsenic were not detected in our samples. Mercury was present, but at levels far below any toxic threshold. This supports the safety of consuming Romanian bay leaves from a mineral contamination perspective.

The comparison of Romanian to Mediterranean bay leaves samples are presented in Figure 2.

When we compared our LAB data with Moroccan (*Mrabet et al., 2024*) and Algerian (*Guenane et al., 2016*) studies, the Romanian bay leaves are consistently richer in macro- and microelements. This observation might be explained by the soils of western Romania, which are relatively fertile and rich in base cations, and by local climate factors that favor mineral uptake. These differences could also contribute to the sensory profile, as many users note that local bay leaves have a stronger, more pungent aroma than imported ones, and mineral nutrition may play a role in essential oil biosynthesis.

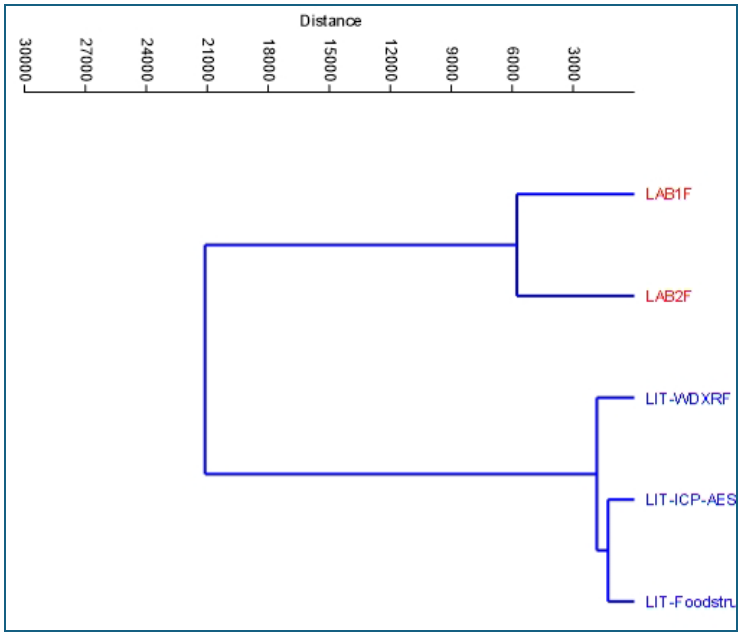

Fig. 2 - Cluster Analysis of Data using Ward's Method based on Euclidian Distances

Legend: LAB1F= dried bay leaves analyzed in our laboratory using XRF; LAB2F= fresh bay leaves analyzed in our laboratory using XRF; LIT-ICP-AES = literature data – minerals detected by ICP-AES, LIT-WD-XRF= literature data – minerals detected by WD-XRF; LIT-Foodstruct = minerals data of bay leaves from Foodstruct.com

Ward's method is a hierarchical clustering technique that groups samples step by step, minimizing the variance within clusters (https://online.stat.psu.edu/stat505/lesson/14/14.7). The Euclidean distance is used as a measure of similarity: samples with smaller "distances" in their mineral composition are considered more identical (*Levy, A. at al, 2025*).

The clustering confirms the distinctive mineral "fingerprint" of Romanian bay leaves, separating them from Mediterranean references (*Guenane, H. at al,2016, Mrabet, A. at al, 2024, https://foodstruct.com/food/bay-leaf)* and also helps which minerals behave in similar ways (e.g., K and Ca

as dominant macronutrients; Zn and Cu as closely related trace metals). Practically it proves that environmental conditions in Dumbrăvița, Timiș county led to a unique mineral and aromatic profile.

Influence of minerals and climatic conditions on adaptation

A unique aspect of our study is that the analyzed bay tree has been growing outdoors in Dumbrăvița (Timiș County) for several winters, surviving cold spells down to –12 °C without damage. This is unusual for a Mediterranean evergreen but can be explained by a combination of mineral nutrition and microclimatic protection. The plant is located just 4–5 m from the house wall, benefiting from residual heat and reduced wind exposure. It is also sheltered by a tulip tree (Liriodendron tulipifera) (*https://www.plante.md/ro/catalog/listvennyie-rasteniya/liriodendron-tulipifera-tulip-tree*), a silver fir (Abies concolor), and a fig tree (Ficus carica), which together act as a living windbreak and buffer against frost. This neighborhood of plants forms a micro-ecosystem that softens temperature extremes, stabilizes humidity, and prevents radiative cooling on cold nights.

Mineral composition may further reinforce this adaptation. High Ca and K improve cell membrane stability and osmotic regulation under cold stress, while Mn and Zn strengthen antioxidant defenses against oxidative bursts triggered by frost (*Zhou L. at al 2025*). In effect, the plant's nutritional richness and its protected microclimate act synergistically to extend its ecological range into temperate Central Europe.

CONCLUSIONS

The present study shows that bay laurel leaves grown in Dumbrăvița, Timiș County are richer in key minerals (potassium, calcium, manganese, and copper), than values commonly reported in Mediterranean studies. This mineral enrichment not only enhances the nutritional value of the leaves but also supports the biosynthesis of volatile compounds, offering a clear explanation for the spicier aroma and stronger flavor noted by consumers.

Ecological observations confirm that the tree has successfully adapted to local winters, surviving temperatures of −12 °C, thanks to both its protective microclimate (neighboring trees and proximity to the house wall) and its robust mineral profile that strengthens stress tolerance. Together, these findings highlight the potential of Romanian bay leaves as a distinctive, safe, and high-quality product with both culinary and functional benefits.

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CAPITALIZING ON CLIMATE-IMPACTED AGRICULTURAL AREAS WITH *CHAENOMELES* FRUIT SHRUBS
/
VALORIFICAREA SUPRAFEȚELOR AGRICOLE AFECTATE DE SCHIMBĂRILE CLIMATICE CU ARBUȘTI FRUCTIFERI *CHAENOMELES*

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Keywords: *Chaenomeles japonica, marmalade, sensory analysis*

ABSTRACT

The interest in dietary intake of polyphenolic compounds has motivated the food industry to include new sources in the human diet. Chaenomeles shrubs (Japanese quince), are widespread throughout the world, originating from Southeast Asia, mainly from China and Japan, the fruits of the shrub are valued in traditional Chinese medicine for their medicinal properties, including antioxidant, anti-inflammatory, immunomodulatory, antiviral, antibacterial, antihyperglycemic and antihyperlipidemic effects (Zhang et al., 2014). Since the fruits are unsuitable for fresh consumption (characterized by hardness, high acidity and astringency), their exploitation for food purposes has been achieved by producing processed forms, such as juices, candied fruits, jams, jellies and chips (Rumpunen et al., 2003). It is common practice for developers of new food products in a target market to evaluate their impact on consumers. The simplest possible compositional structures were used, processing the Japanese quince fruits in the form of jam and marmalade. The new product, Japanese quince marmalade, has a positive overall image, with 88.4% of the subjects surveyed appreciating the main sensory characteristics. The overall acceptability score for the reformulated Japanese quince marmalade samples was for the cinnamon sample.The new products have a positive overall image that justifies the establishment of Chaenomeles shrub crops in Romania.

REZUMAT

Interesul pentru aportul alimentar de compuși polifenolici a motivat industria alimentară să includă noi surse în dieta umană. Arbuștii de Chaenomeles (gutui japonez), sunt răspândiți în întreaga lume, originari din Asia de Sud-Est, în principal din China și Japonia, fructele arbustului sunt apreciate în medicina tradițională chineză pentru proprietățile lor medicinale, inclusiv efecte antioxidante, antiinflamatorii, imunomodulatoare, antivirale, antibacteriene, antihiperglicemice și antihiperlipidemice (Zhang et al., 2014). Deoarece fructele sunt improprii consumului în stare proaspătă (caracterizate prin duritate, aciditate ridicată și astringență), valorificarea lor în scopuri alimentare s-a realizat prin producerea de forme procesate, cum ar fi sucuri, fructe confiate, gemuri, jeleuri și chipsuri (Rumpunen et al., 2003). Este o practică obișnuită ca dezvoltatorii de noi produse alimentare pe o piață țintă să evalueze impactul acestora asupra consumatorilor. Au fost utilizate cele mai simple structuri compoziționale posibile, procesând fructele de gutui japonez sub formă de dulceață și marmeladă. Noul produs, marmeladă japoneză de gutui, are o imagine generală pozitivă, 88,4% dintre subiecții chestionați apreciind principalele caracteristici senzoriale. Scorul global de acceptabilitate pentru probele reformulate de marmeladă japoneză de gutui a fost la proba cu scorțișoară. Noile produse realizate au o imagine generală pozitivă ce justifică înființarea culturilor de arbust Chaenomeles în România.

INTRODUCTION

The interest in the dietary intake of polyphenolic compounds has motivated the food industry to include new sources of polyphenolic compounds in the human diet. The shrubs of Chaenomeles (Japanese quince), family Rosaceae, with their four species (Chaenomeles cathayensis, Chaenomeles speciosa, Chaenomeles thibetica, and Chaenomeles japonica) are widespread throughout the world, originating from Southeast Asia, primarily in China and Japan. The fruits of the shrub are valued in traditional Chinese

medicine for their medicinal properties, including antioxidant, anti-inflammatory, immunomodulatory, antiviral, antibacterial, antihyperglycemic, and antihyperlipidemic effects *(Zhang et al., 2014).* Originally cultivated in Europe as an ornamental shrub, the chemical composition of Chaenomeles fruits has been studied. The abundance of phytochemical compounds in the Chaenomeles plant *(Ruoling et al., 2023)* suggests that the plant is suitable for use in the production of dietary supplements for the prevention or early treatment of metabolic syndrome disorders.

As a result, Chaenomeles are used in several industries to drive product innovation and support consumer health *(Hongyue et al., 2024).* A high content of organic acids was found in the extracts, being a rich source of phenolic compounds, the dominant group being polymeric proanthocyanidins in a percentage of up to 79% of total polyphenols *(Turkiewicz et al., 2021),* total phenolic acids 175 mg/g of which chlorogenic acid 4.4%, procyanidins 57.8%, (-)-epicatechin 33% *(Strugała et al., 2016). Baranowska-Bosiacka et al. (2017)* found high levels of microelements in fresh fruit: 0.516 Fe, 0.146 Cu, 0.546 Zn, 0.25 Mn, 16.73 Mg, 22.92 Ca, 64.09 P, 249.74 K, expressed in mg/100g dry matter, ascorbic acid 62.7 – 68.8 g/100g, vitamins and carotenoids *(Haizhao et al, 2024),* tannins, oligosaccharides, fiber 1.35-3.88 g/100g. And in the study conducted by (*Turkiewicz (et al., 2021),* it was confirmed that Chaenomeles fruits can be part of a balanced diet, providing vitamins A and E, as well as essential amino acids necessary for the proper functioning of the human body.

According to another study, Chaenomeles seeds are also rich in potassium and microelements (Fe, Cu, Zn, Mn), with nutritional potential *(Turkiewicz et al., 2021).* The review by Marat et al. (2022) highlights the content of phenolic compounds in 5 Chaenomeles varieties: C. speciosa, C. thibetica, C. cathayensis, C. japonica, and C. sinensis. The nutritional value of Chaenomeles fruits has led to the establishment of crops primarily in Lithuania, Estonia, Latvia, Sweden, Finland, and Poland. Since the fruits are unsuitable for fresh consumption (characterized by hardness, high acidity, and astringency), their exploitation for food purposes was achieved through the production of processed forms, such as juices, candied fruits, jams, jellies, and chips *(Rumpunen et al., 2003; Radenkovs et al., 2024).*

The characteristic aroma of Japanese quinces (a combination of citrus, pineapple, and nut aromas) increases their potential for exploitation in the food industry. In Romania, Japanese quince shrubs are cultivated exclusively for ornamental purposes in landscaping. The low agroclimatic requirements, resistance to pests, and minimal fertilization requirements make the Japanese quince a suitable choice for cultivation, particularly in organic farming *(Marat et al., 2022).* The shrubs can grow on nutrient-poor soils, are resistant to both water excess and deficiency in the soil, as well as to frost and high temperatures, for short periods.

The potential for the development of Chaenomeles crops is high in areas strongly affected by climate change (approximately 30% of the country's agricultural area). These hilly areas are located in Transylvania, Maramureș, and the Subcarpathian hills (approximately 5 million hectares) *(Badiu et al., 2020*). These lands are characterized by natural vegetation (meadows and natural pastures), forested with shrubs and traditional orchard plantations, and intensive cereal crops. In the Eastern Subcarpathians, the climate is sharply continental, with moderately warm summers (averaging 19°C, with an extreme of 40°C) and winters characterized by average temperatures ranging from -5.5°C to -6°C (with an extreme of -25°C) *(Chiţu et al., 2010; Chiţu et al., 2023)*.

The intensification of meteorological phenomena due to climate change has resulted, in recent years, in decreases in fruit production from traditional orchards and in the productivity of cereal crops. *(Coman et al., 2023).* The requirements of the Japanese quince shrub are conducive to establishing crops in the hilly areas of Romania affected by climate change, to valorize agricultural areas economically.

The Japanese quince fruit is not known in Romania as a food, either in fresh or processed form. It is common practice for developers of new food products in a target market to evaluate their impact on consumers. It is necessary to consider the attitudes and expectations of potential consumers, as they influence the sensory quality of products by evaluating the perceived intrinsic and extrinsic characteristics.

This study was conducted to evaluate the potential for valorizing Japanese quince fruits, considering their nutritional value. The simplest possible compositional structures were used, processing Japanese quince fruits in the form of jam and marmalade. The test samples were produced using traditional technology and then reformulated to reduce the sugar content and eliminate the intense sour taste.

MATERIALS AND METHODS

1. Materials

1.1 Raw materials and ingredients for test product execution

Japanese quince fruits were harvested from the landscaping of INCDBA IBA Bucharest in October 2024. The fruits were harvested ripe, with a light-yellow color and a characteristic, persistent aroma. They were processed by removing the seminal cavity and seeds, slicing, vacuum packaging, and freezing at -20°C until use in the test products. The compositional dilution of fruits was made with apples from the local varieties Iohnatan and Golden Delicious, fresh and purchased from the local market. Pectin and stevia extract were purchased from the Food Ingredients Romania branch, and sugar, fructose, lemons, and cinnamon were purchased through the commercial network.

1.2 Reagents

The reagents used, of analytical purity, for the physico-chemical determinations were purchased from the company laboratory Bucharest.

2. Methods

2.1 Processing Japanese quince into food products

a) Three types of jams were obtained according to traditional processes from thawed Japanese quince fruits and: a mixture of fresh apples with sugar (product code 587) / or fructose (product code 340)/ or stevia extract (product code 289), pectin, and lemon juice. The fruit mixture was brought to a boil with sweetener, left to rest for 3 hours to facilitate the osmosis process, finely chopped, and pectin was added and concentrated to a total soluble substance value < 35°Brix. The samples were differentiated by the sweetener used: sugar, fructose and sugar dilution with stevia extract (Table 1).

b) Japanese quince marmalade (product code 578), a traditional product, was produced over an open fire, by immersing thawed Japanese quince fruits and fresh Jonathan apples in sugar syrup, with a fruit:sugar ratio of 1:1 (kg/kg). The mixture was brought to a boil, finely chopped and concentrated to a total soluble substance value of approximately 65°Brix.

Table 1

Compositional structures of test products from Japanese quince

Sample code / Composition, %	587	340	289	578	251	612
Japanese quince fruit	31.50	32.40	33.95	22.12	35.93	35.78
Apples	26.80	27.60	33.95	22.12	29.94	24.66
Sugar	20.40	-	6.35	44.25	14.97	18.13
Fructose	-	15.00	-	-	-	-
Stevia extract	-	-	1.50	-	0.84	1.61
Pectin	1.17	1.50	1.70	-	1.50	1.21

where: 587 = jam with sugar; 340 = jam with fructose; 289 = jam with stevia; 578 = traditional *Japanese quince marmalade*; 251 = stevia *Japanese quince marmalade* with lemon; 612 = stevia Japa*nese quince marmalade* with cinnamon.

c) For the reformulated Japanese quince marmalade samples (product code 251 and product code 612), the compositional dilution was made with Golden Delicious apple, the sugar dilution with stevia extract, pectin, and flavorings: lemon peel and cinnamon. (Table 1) The manufacturing process was the one used for Japanese quince marmalade, a traditional method, up to a total soluble substance value of < 50°Brix.

2.2 Analytical determinations

a) Determination of total soluble substances (%Brix) was carried out with a classic ABBE AR4 Refractometer, manufactured by KRUSS Germany, with a measurement range of 0-95% Brix, accuracy of 0.25% Brix, temperature measurement accuracy ±0.5°C, and temperature measurement resolution 0.1°C. The mass of the sample taken for analysis was 5g, which was diluted with distilled water in a ratio of 1:1 and 1:2, depending on the viscosity of the sample.

The calculation:

$$\%Brix = \%Brix\ read\ X\ dilution \quad (1)$$

The readings were performed in duplicate.

b) pH determination, was performed with a digital laboratory pH meter 827 manufactured by Metrohm Switzerland, series 2013. The readings were performed in duplicate, the average of the readings representing the measurement result.
c) Acidity determination was performed according to SR EN 750/2008.
d) Sensory evaluation
The sensory analysis for assessing the acceptability of the new products was conducted through hedonic tests using scoring scales. The groups of evaluators consisted of untrained individuals, aged between 20 and 65, of both genders.

RESULTS

The test products were subjected to physicochemical and sensory analysis using hedonic acceptability tests and descriptive analysis tests between assortments of the same product (Japanese quince jam) as well as by comparison with a control product (Cydonia oblonga quince jam, sample code 341). Cydonia oblonga quince jam is a traditional product manufactured and marketed by S.C. Annabella Fabrica de Conserve Râureni S.A., Romania.

3.1 Analytical determinations

The chemical characteristics of the test samples (jam and Japanese quince marmalade) are given in Table 2.

Table 2

Chemical characteristics of test products Japanese quince jam and marmalade

Sample code / Chemical characteristics	587 (Z)	340 (F)	289 (S)	341	578	251	612
SST (°Brix)	34.58	33.09	15.81	60.50	67.85	25.80	46.08
pH	2.87	2.94	2.95	3.00	3.02	3.12	3.11
Free acidity (% acid citric)	1.45	1.72	2.0	0.58	1.04	1.68	1.37

where: 340 = fructose jam; 587 = jam sugar; 289 = stevia jam; 341 = control; 578 = traditional *Japanese quince marmalade*; 251 = stevia Japanese quince with lemon; 612 = stevia *Japanese quince marmalade* with cinnamon.

The chemical composition analysis (Table 2) is correlated with the compositional structure (Table 1).

For the test products Japanese quince jam, it is found that by increasing the percentage of Japanese quince fruits in the composition, the pH of the samples has values within very narrow limits: ± 0.04 pH. The free acidity increases proportionally with the increase in the content of Japanese quince fruits, the increase being by a percentage of approximately 27% for each 1% addition of Japanese quince fruits. The difference between the samples was given by the content in SST, where sample 289 (with the addition of stevia extract) was 45.7°Brix compared to sample 587 (with the addition of sugar) and 47.78°Brix compared to sample 340 (with the addition of fructose).

For the reformulated Japanese quince marmalade test samples, the optimization of the compositional structure was considered by increasing the content of Japanese quince fruits and decreasing the level of SST in the product. An increase in the total fruit content by 12.63% (251) and 16.2% (612) and in the content of Japanese quince fruits by 13.8% (251) and 13.66% (612) was obtained compared to sample 578. (Table 1).

The samples were chemically characterized simultaneously with a sample of Cydonia quince marmalade, purchased from the commercial network (sample code 341). Reducing the amount of added sugar by 29.28% (251) and 26.12% (612) reduced the SST content by 42°Brix (251) and 21.77°Brix (612) compared to that of sample 578 (67.85°Brix). (Table 2)

3.2 Sensory analysis

The sensory analysis of Japanese quince products was carried out in three steps according to the scheme in Figure 1.

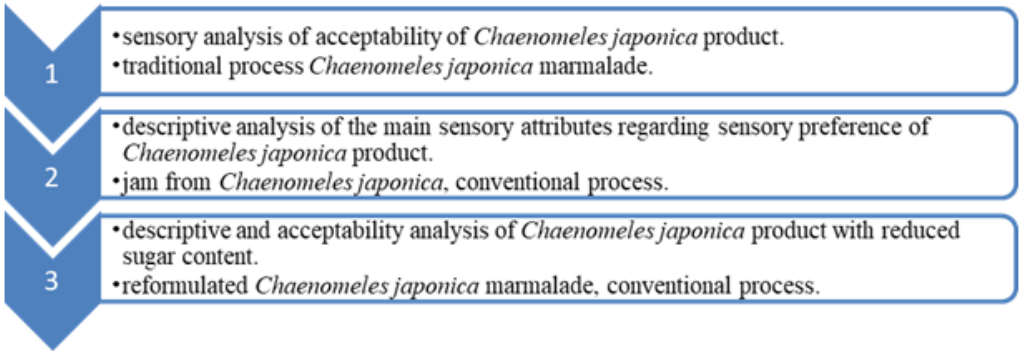

Fig. 1 - Sensory analysis scheme for products made from Japanese quince (*Chaenomeles japonica*)

1) The sensory quality analysis of the Japanese quince marmalade product (code 578), a traditional process, was carried out through a hedonic acceptability test for a unidimensional result. A 5-point Likert scale was used: 1-total disagreement; 2-disagreement; 3-indifferent; 4-agreement and 5-total agreement, through questions of appreciation of the perceptible sensory characteristics of the product: appearance, color, taste, flavor. The test was carried out on a number of 22 untrained subjects, grouped by age (under 30 years (8 subjects) _ 30 - 40 years (8 subjects) _ over 40 years (6 subjects)).
The score of the 4 sensory attributes resulted from calculating the algebraic sum of the opinions of the surveyed subjects. The result classified (Figure 2), in descending order, the sensory quality assessment of the Japanese quince marmalade sample, traditional process, as follows:
Color = 4.64 > Appearance = 4.59 > Flavor = 4.36 > Taste = 4.09;

The Global Score was calculated as the simple arithmetic mean of the partial scores, with a value of 4.42. The product has a positive overall image, with 88.4% of the surveyed subjects appreciating the main sensory characteristics of the new product. The global score, by age group indicates the highest degree of acceptability belonging to the age group under 30 years.

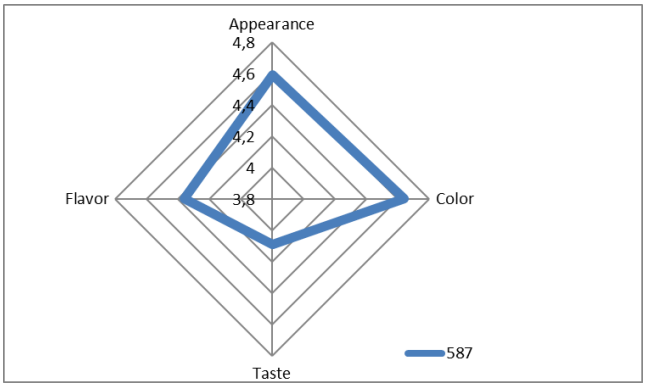

Fig. 2 - Sensory assessment of the Japanese quince marmalade sample

2) In order to establish a relationship between the main sensory attributes of the product (appearance, consistency, color, taste, aroma) and the sensory preference expressed by consumers, a product diversification from Japanese quince fruit was used by making three jam samples: code 587 - with added sugar, code 340 - with added fructose and code 289 - with added sugar and stevia extract. The objective of the test was to identify the perceptions underlying consumer preferences through descriptive assessment. A number of 13 subjects of both genders, aged between 25 and 65 years, participated in the test. The questionnaire used was developed in five stages of appreciation, well defined for each sensory characteristic, in order to identify the perception of each general sensory attribute underlying consumer preference. The information obtained by calculating the average score regarding the assessment of multiple general properties of Japanese quince jam samples is presented in Figure 3.

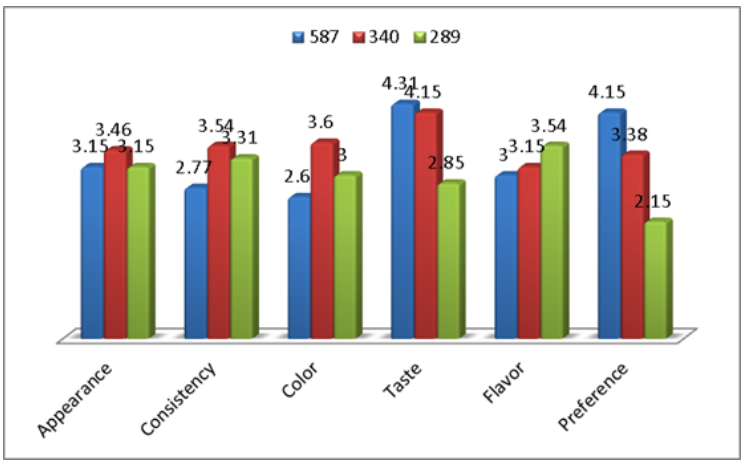

Fig. 3 - Score on the appreciation of multiple general properties of Japanese quince jam samples, where: 587 = Japanese quince jam with added sugar; 340 = Japanese quince jam with added fructose; 289 = Japanese quince jam with added sugar and stevia extract.

It is observed from Figure 4 that in the top of preference for the taste attribute the highest score was assigned to the sample with added sugar (587). The sensory attributes with visual evaluation (appearance, consistency and color) had the best score for the sample with added fructose (340), and the aroma attribute classified, with the best score, the sample with added stevia (251). It was found that the sample with added sugar (587) accumulated the best score regarding preference.

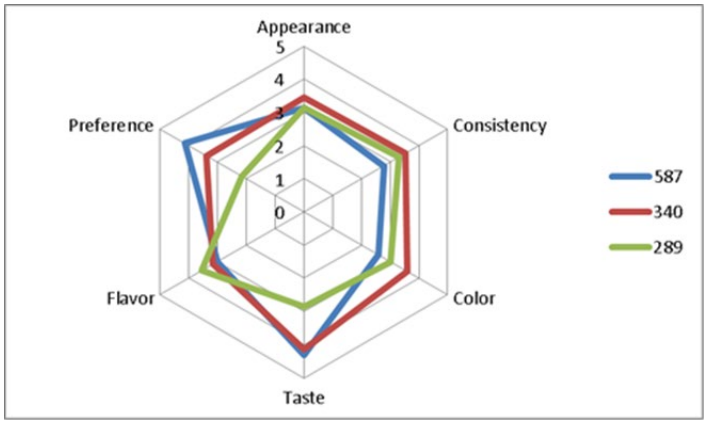

Fig. 4 - Sensory profile descriptive analysis of Japanese quince jam samples, where: 587 = Japanese quince jam with added sugar; 340 = Japanese quince jam with added fructose; 289 = Japanese quince jam with added sugar and stevia extract.

When assessing the sweet and sour taste (Figure 5) the subjects appreciated the perception of sour taste as superior to sweet taste for all samples. The jam sample evaluated with the most balanced ratio of sour taste / sweet taste was the sample with added fructose 340 = 1.11 < 587 = 1.14 < 289 = 1.31.

The Global Product Appetite Score (GPS) was calculated as the simple arithmetic mean of the partial scores. The global score thus calculated ranks the Japanese quince jam samples in the following order: 3.58 (340) > 3.17 (289) > 3.16 (587). Jam sample 340 has a higher score than jam sample 587 for the attribute's appearance (0.31 Pm), consistency (0.77 Pm) and aroma (0.15 Pm) (Figure 5) by 1.07 Pm. for the taste attribute, outperforming sample 587. It is found that the SG of the samples regarding acceptability differs from the expressed option regarding Preference (4.15 (587) > 3.38 (340) > 2.15 (289)).

Overall, the products have a high degree of acceptability, with the surveyed subjects positively appreciating, in percentages of 71.6% (340), 63.4% (289) and 63.2% (587) the main sensory characteristics of the new products, in the three compositional variants.

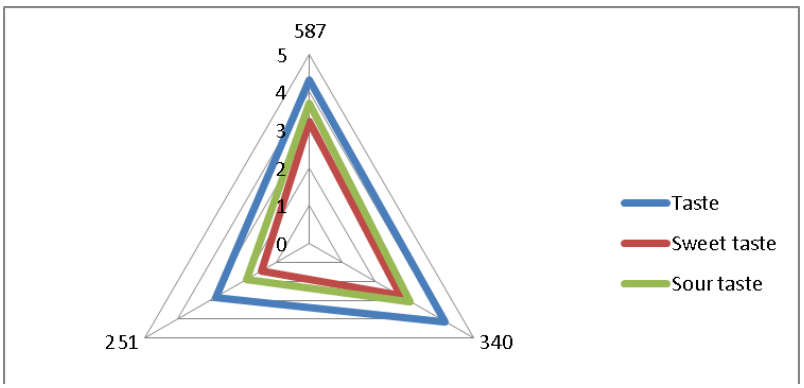

Fig. 5 - Average score of sour taste and sweet taste, where: 587 = Japanese quince jam with added sugar; 340 = Japanese quince jam with added fructose; 289 = Japanese quince jam with added sugar and stevia extract.

3) Sensory analysis of reformulated Japanese quince marmalade samples.

A five-point assessment questionnaire was used to analyze the sensory profile and consumer preference, well-defined for each sensory characteristic. The test was attended by 30 consumers, trained on (the evaluation procedure and questionnaire completion) for the perception of each general sensory attribute), aged < 30 years (18 consumers), 30 – 40 years (6 consumers) and > 40 years (6 consumers), of both genders.

By calculating Pm, the appreciation of the main sensory characteristics (Figure 6) of the reformulated Japanese quince marmalade samples (251 and 612) was evaluated compared to a Cydonia quince marmalade sample (341), purchased from the local market.

The sensory profile obtained is presented in Figure 6.

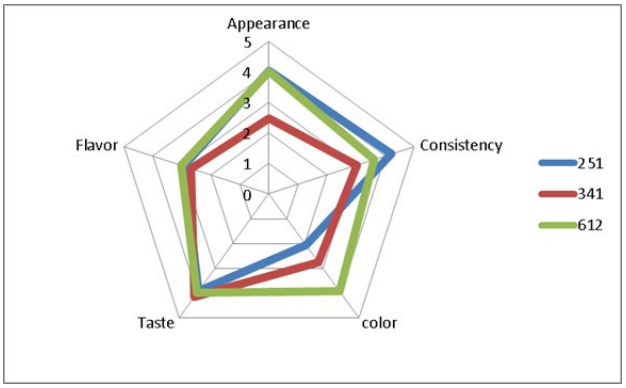

Fig. 6 - Sensory profile descriptive analysis of main sensory attributes of Japanese quince marmalade, where: 251 = Japanese quince marmalade formulation variant 1 (lemon peel), 612 = Japanese quince marmalade formulation variant 2 (cinnamon); 341 = Cydonia quince marmalade (control).

The result of the descriptive sensory analysis classifies the main sensory attributes (Figure 6) of the reformulated Japanese quince marmalade samples as follows:

Appearance: sample 251 was preferred with a slight difference in score (+0.6 Pm) compared to sample 612: described as fine, homogeneous paste, clear visual appearance.

Consistency: sample 251 was the most preferred being the firmest, with a total fruit content of 65.87%, the highest percentage of pectin and the lowest SST content = 25.8°Brix.

Color: sample 612 was the most preferred, the addition of cinnamon imitates the color of Cydonia quince marmalade from the commercial network (341), a traditional product.

Taste: sample 341 was the most preferred, possibly due to its more intense sweet taste with the highest SST content = 60.50°Brix compared to 251 = 25.8°Brix and 612 = 46.08°Brix. The differences in average score obtained by the three samples are not significant (± 0.12):

4.17 (341) > 4 (612) > 3.93 (251)

Aroma: sample 612 obtains the best average score = 3.03, but at a value very close to the two samples 2.93 (251) and 2.67 (341). In traditional cuisine, the aroma of cinnamon is associated with quince and apple fruits, the addition of spice having an important weight in the level of appreciation of the aroma.

The descriptive analysis for the taste attribute, resulting from the average score calculation, has the sensory profile in Figure 7.

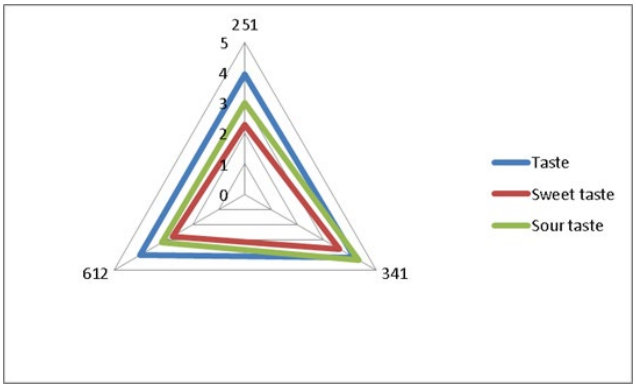

Fig. 7 - Sensory profile of the taste attribute of reformulated Japanese quince marmalade. Where: 251 = reformulated Japanese quince marmalade variant 1 (lemon peel), 612 = reformulated Japanese quince marmalade variant 2 (cinnamon); 341 = Cydonia quince marmalade (control).

It is observed from Figure 7 that the Japanese quince marmalade samples with the most balanced average score of the sour taste / sweet taste ratio were, in ascending order, 1.14 (341) < 1.2 (612) < 1.32 (251), a sensory evaluation that was perceived faithfully to the free acidity value of the samples: 1.04 (341) < 1.37 (612) < 1.68 (251). (Table 2)

The significant differences in sensory quality between the three samples were recorded in the sensory attributes consistency and color as a result of the difference in SST content (Table 2) and the color of the spices.

The global acceptability score was calculated similarly to the jam samples, as a simple arithmetic mean of the partial scores. The overall sensory quality assessment score classifies the reformulated Japanese quince marmalade sample with cinnamon (612) with the best average score (3.72), according to Figure 6.

It can be concluded that consumer preference recommends for reformulating Japanese quince marmalade (by increasing the content of Japanese quince fruits and decreasing the level of SST) a Japanese quince fruit / apple ratio of 1.45 and a reduction in sugar content by approximately 26% compared to the composition of Japanese quince marmalade with the traditional process (578). (Table 1) Consumers participating in the study appreciated the sensory quality of the marmalade samples, in both variants, by a percentage of 74.4% (612) > 68.8% (251) > 60.4% (341), outperforming the Cydonia quince marmalade currently available in the commercial network.

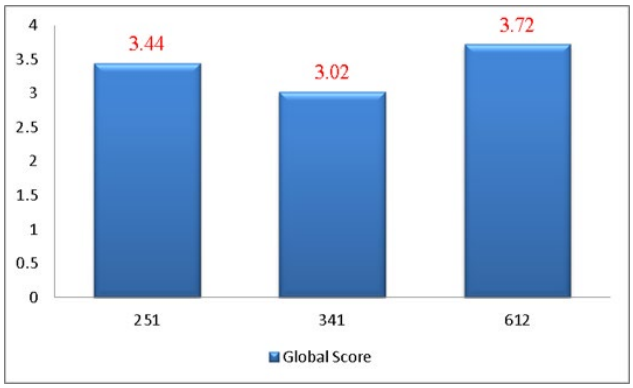

Fig. 8 - Classification, according to the global score, of the sensory quality of the reformulated *Japanese quince marmalade* samples, where: 251 = *Japanese quince marmalade* formulation variant 1 (lemon peel), 612 = *Japanese quince marmalade* formulation variant 2 (cinnamon); 341 = Cydonia quince marmalade (control)

CONCLUSIONS

The fruits of Chaenomeles shrubs (Japanese quince) are a significant source of compounds with high biological value that can contribute to the nutritional increase of the diet, due to the abundance of phytochemical compounds and the high content of microelements. The study evaluated the potential for the exploitation of Japanese quince fruits in Romania, in order to establish Chaenomeles shrub crops. The study

was based on making compositional structures as simple as possible by processing the fruits in the form of jam and marmalade. The sensory analysis of the new products was carried out using the 5-point Likert scale as a sensory study instrument for calculating the Global Score and STAS 12656-88: Sensory Analysis, Scoring Scale Methods, for calculating the average score for classifying the quality of sensory attributes. The study was carried out in three stages on a number of 65 untrained subjects, aged between 20 and 65 years of both genders.

The Japanese quince fruit jam made in three variants (with fructose, sugar and stevia extract) obtained a positive overall score, with the surveyed subjects appreciating the main sensory characteristics of the jam in percentages of 71.6%; 63.2% and 63.4%.

The marmalade product was made in three variants of sugar content: 44.25%; 18.13% and 14.97%. The calculation of the global score on acceptability resulted in a percentage of 88.4%; 74.4% and 68.8% of subjects who positively appreciated the sensory quality of the Japanese quince marmalade product. For the production of Japanese quince marmalade, consumer appreciation recommends a Japanese quince fruit / apple ratio of 1.45 and the possibility of reducing the addition of sugar by approximately 26% - 30% compared to the traditional manufacturing process.

The new products produced have a positive overall image that justifies the establishment of Chaenomeles shrub cultures in Romania.

ACKNOWLEDGEMENT

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DESIGN OPTIMIZATION OF CUTTING BLADES FOR MOWING EQUIPMENT THROUGH COMPARATIVE STUDY USING SOLIDWORKS SIMULATION

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OPTIMIZAREA CONSTRUCTIVĂ A CUȚITELOR PENTRU ECHIPAMENTE DE COSIT PRIN STUDIU COMPARATIV UTILIZÂND SOLIDWORKS SIMULATION

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Keywords: *design study, blade rotor, mowing equipment, design optimization*

ABSTRACT

This study aims to optimize the design of tractor-mounted rotary mower blades for inter-row mowing by building on insights from prior SolidWorks simulation studies. Previous structural and modal analyses of blade rotors provide critical information on stress distribution, deformation, and material behavior under dynamic operating conditions. Using these findings, the research evaluates how blade geometry—including length, angle of attack, number of blades per drum, and thickness—and material selection influence cutting efficiency, torque, vibration, and overall durability. By applying this knowledge, the study identifies design improvements that enhance performance, reduce mechanical stress, and ensure reliable operation, providing a foundation for developing more efficient and durable rotary mowing equipment suited to modern agricultural demands.

REZUMAT

Acest studiu își propune optimizarea designului lamelor pentru cositori rotative tractate, utilizate la cosirea între rânduri, prin valorificarea rezultatelor studiilor anterioare realizate în SolidWorks. Analizele structurale și modale preexistente ale rotoarelor lamelor furnizează informații esențiale privind distribuția tensiunilor, deformațiile și comportamentul materialelor în condiții de operare dinamice. Pe baza acestor date, cercetarea evaluează modul în care geometria lamelor — inclusiv lungimea, unghiul de atac, numărul de lame pe rotor și grosimea — și selecția materialelor influențează eficiența tăierii, cuplul, vibrațiile și durabilitatea generală. Aplicând aceste cunoștințe, studiul identifică îmbunătățiri de design care cresc performanța, reduc solicitările mecanice și asigură funcționarea fiabilă, oferind un fundament pentru dezvoltarea unor echipamente de cosire rotative mai eficiente și mai durabile, adaptate cerințelor moderne ale agriculturii.

INTRODUCTION

In modern agricultural mechanization, tractor-mounted rotary drum mowers play a vital role in forage harvesting systems. These machines use fast-rotating blades to cut grass and other vegetation efficiently. Compared with traditional sickle-bar mowers, rotary drum mowers offer higher cutting capacity, reduced vibration, and improved stubble uniformity *(Celik et al., 2023; Wu et al., 2023).* The performance of such mowers depends largely on the geometric and structural characteristics of the blades, including length, angle of attack, number of blades per drum, and rotational speed *(Celik et al., 2023).* Figure 1 shows a representative rotary mower blade model illustrating the primary geometric parameters that influence cutting performance.

Fig. 1 - Tractor mounted rotary drum mower model
(Celik et al., 2023)

The geometry and material of mower blades are crucial to both efficiency and durability. Studies have shown that twisted or inclined blades can lift crops before shearing, resulting in cleaner cuts and lower energy demand *(Wu et al., 2023; Uzoma & Briggs, 2019).*

Conversely, worn or sub optimally shaped blades significantly increase drag and fuel consumption; Refai et al., (2023) reported that worn drum mower blades increased fuel use by 67% and carbon dioxide emissions during alfalfa mowing. The mechanical performance of blades, therefore, strongly depends on their material properties—hardened steels and advanced alloys are often selected to improve wear resistance and service life *(El-Baily, 2022; Alkaddour 2025).*

From a mechanical standpoint, mower blades are subjected to intense dynamic loads during operation. Bartoň (2019) demonstrated that the oscillatory motion of drum mower blades is closely linked to vegetation properties and blade stiffness, emphasizing the need for structural and modal analysis in design.

Similarly, in a previous research study performed modal and structural analysis on a mower blade rotor using SolidWorks Simulation, identifying critical stress zones and natural frequencies under working conditions. These findings underscore the value of computer-aided engineering (CAE) in optimizing agricultural cutting equipment, it is also a good starting point for design optimization *(Harabagiu et al., 2024*).

Advancements in simulation technology have facilitated the optimization of mower blades using SolidWorks Simulation and Design Study modules. These tools allow for the variation of geometric and material parameters to evaluate stress distribution, deformation, and natural frequency. For instance, Revi et al., (2016) used computational fluid dynamics (CFD) and finite element analysis (FEA) to refine the aerodynamic profile of a rotary mower blade. Similarly, Pandey et al., (2021) modeled a rotary tiller blade in SolidWorks and performed fatigue analysis in ANSYS to determine optimal dimensions for reducing power consumption.

Figure 2 illustrates key blade geometry parameters—the cutting angle and thickness—both of which strongly influence torque, stress, and energy efficiency *(Uzoma & Briggs, 2019).* Considering the reviewed studies, the present work focuses on the design optimization of cutting blades for a tractor mounted rotary mower through a comparative study using SolidWorks Simulation.

The research aims to identify the optimal combination of blade geometry and material to minimize stress and vibration while maximizing cutting efficiency and structural reliability, building directly on the methodology and findings of our previous study, we now investigate possible design optimization.

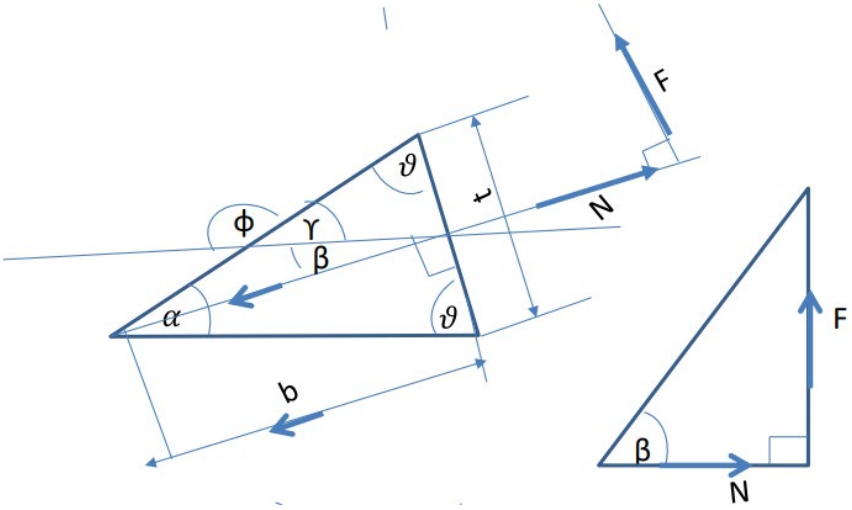


Fig. 2 - Geometric representation of blade cutting angle and thickness
(Uzoma & Briggs, 2019)

MATERIALS AND METHODS

The materials and research methodology for this study involve the analysis of scientific literature, including summaries from specialized sources such as Thomson ISI, ScienceDirect, ResearchGate, and Google Scholar. The research uses an already existing 3D CAD model of the cutting blade designed in SolidWorks and previous simulation results. The optimization process relies heavily on insights obtained from previous studies *(Nandish et al., 2019; Wang et al., 2024)* and prior simulation results of our blade and blade rotor.

These earlier investigations provided detailed information on stress distribution, deformation patterns, vibration behavior, and critical failure zones under operating conditions (Figure 3).

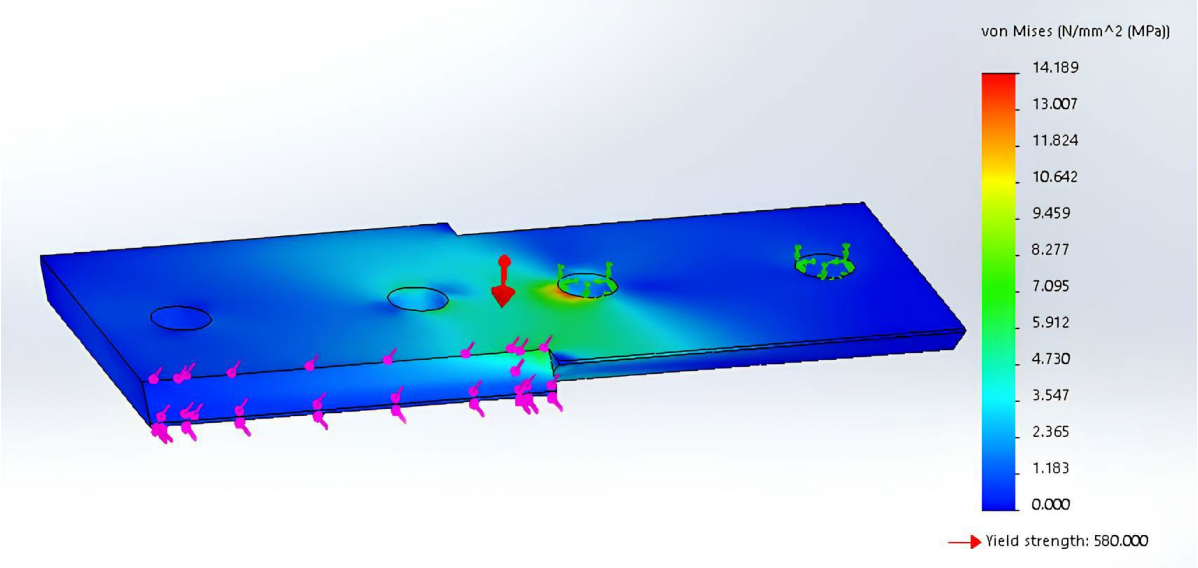


Fig. 3 - Stress results on the cutting blade

All design studies and optimizations reported in this work were created and executed using the Design Study functionality built into SOLIDWORKS. The Design Study environment provides two distinct but related computational paradigms for exploring parametric design spaces: an evaluation paradigm in which discrete sets of parameter values are enumerated to form multiple scenarios that are individually evaluated, and an optimization paradigm in which variables are specified as continuous ranges or discrete choices and the software iteratively searches the design space for combinations that satisfy user-defined constraints while optimizing one or more objectives.

Evaluation is appropriate to exhaustively or selectively test a manageable number of discrete combinations, whereas optimization is more appropriate when continuous exploration and automated search are required to locate optimal subject to constraints (2023 Web Help, Dassault Systèmes).

Prior to the construction of any study, model preparation and prerequisite elements were established within the SOLIDWORKS.

Figure 4 shows the parameters used as variables, they were defined as dimension-driven model parameters and persistent sensors were created to report quantities of interest such as mass properties, key dimensions, or, when required, simulation outputs. Simulation-derived sensors were required, our previous study was used as an initial simulation study, this provides the optimization module with a baseline simulation that it can re-solve for each scenario or iteration. Study metadata (including the results folder and study quality settings) were set at study creation so that output files, intermediate results, and logging followed a reproducible file structure.

The SOLIDWORKS documentation describes the recommended practice of defining parameters and sensors before creating the study, and explains how study properties influence result storage and fidelity.

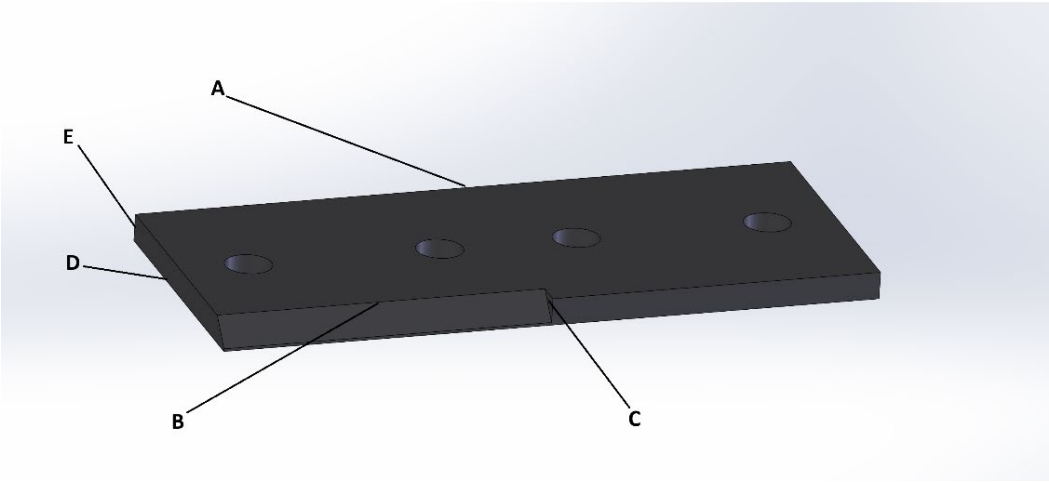


Fig. 4 - Most influential design parameters of the blade

The workflow employed to build each study followed the canonical sequence implemented in the SOLIDWORKS Design Study property managers and user interface. A new Design Study tab was created within the model, after which variables were linked to model parameters and sensors were associated with the physical quantities and simulation outputs of interest; variables were specified as discrete value lists, but also as continuous ranges with different step sizes, and sensors were marked as objectives.

For optimization studies variables were supplied as continuous ranges and as mixed discrete sets, and the Optimization checkbox engaged the solver that iteratively sampled the design space with the aim of satisfying constraints while minimizing the chosen goal sensors, in our case the factor of safety.

Operational parameters and solver limit important to reproducibility and to the interpretation of results were recorded and controlled. The evaluation/design-scenario module imposes a practical upper bound on the number of enumerated scenarios; the documentation specifies that up to 4,096 scenarios can be generated and evaluated in a single evaluation study, for our study 247 scenarios were made. For optimization studies the software imposes limits on the number of design variables and the combined count of goals plus constraints; the official guidance states a maximum of 20 design variables and a total of 20 constraints and goals combined, our study used a total of 5 variables and only 3 constraints and goals combined.

Study quality was set to high, these were chosen to balance computational cost and numerical fidelity; the documentation notes that quality settings affect available post-processing features (for example, certain local-trend graphs are not available under specific combinations of high quality and discrete-only variables) and thereby influence the types of sensitivity analyses that can be performed directly in the Design Study interface.

In the present study, the optimization of the blade design was carried out with five key design variables, as previously mentioned, each selected to capture critical aspects of the geometry and functional performance. The first variable, blade width, was defined over a discrete range from 50 to 150 mm with increments of 50 mm, representing variations in lateral size that influence cutting efficiency and structural rigidity.

The second variable, cutting angle, was considered as three discrete values: 30°, 45°, and 60°, reflecting the angular orientation of the blade edge relative to the material and its effect on cutting performance and load distribution. Blade thickness, the third variable, was varied across 4, 8, and 10 mm, capturing the influence of cross-sectional robustness on mechanical strength and resistance to deformation. Blade length was treated as a continuous variable within the range 240 to 480 mm, incremented in steps of 120 mm, accounting for the longitudinal reach and leverage of the blade during operation.

Finally, the ratio of cutting surface, expressed as the proportion of the blade length that constitutes the effective cutting edge, was varied from 0.25 to 0.75 in steps of 0.25, representing different distributions of cutting versus non-cutting regions along the blade. Together, these variables were systematically incorporated into the SOLIDWORKS Optimization Module, enabling the iterative solver to explore the multidimensional design space and identify configurations that optimize performance objectives while satisfying defined constraints.

Finally, for scientific validity, computational results obtained from Design Study optimization were subjected to independent verification and engineering judgment before being reported. Optimized designs were examined for manufacturability, checked against unmodeled constraints, and re-evaluated with refined mesh or higher study quality in the linked simulation study.

RESULTS

For this study it was used the Design Study Add-in built within SolidWorks. In order to improve the blade design, previous structural simulations using different loads in order to simulate the use of the machine in different environments. We used the original model of the blade with the length of the cutting edge of 120 mm, a width of 100 mm, a thickness of 10 mm and a 45-degree cutting angle.

The first design study takes into account previous results of the stress and deformation on the blade during alfalfa harvesting, our previous study was used in order to determine the value of this stress and deformation, the cutting edge length, the blade width, the cutting angle and blade thickness were modified in order to achieve a much better factor of safety, and less deformation on the blade, the mass of the blade was also monitored during our study in order to find a lighter design possibility to reduce the manufacturing costs.

First step was to define the variables and their specific values within SolidWorks Design Study (Figure 5).

Name	Type	Value	Units
A	Range with Step	Min:50 Max:150 Step:50	mm
B	Discrete Values	30°, 45°, 60°	deg
C	Discrete Values	4, 8, 10	mm
D	Range with Step	Min:240 Max:480 Step:120	mm
E	Range with Step	Min:0.25 Max:0.75 Step:0.25	N/A

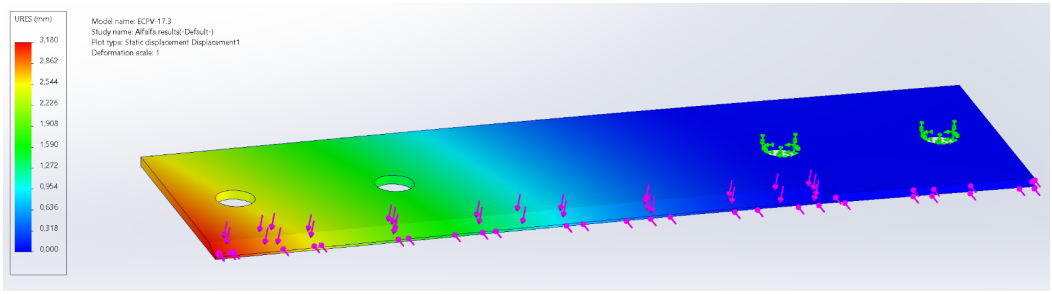
Fig. 5 - Setting up the Design Study

The goal of the Design Study was to achieve a much lower Factor of Safety (FOS), while maintaining the structural properties of the blade. At the end of the study process, we achieved a blade design that has a blade thickness of 4, a total length of 360 mm with a cutting edge of 75% of total length, the cutting angle of 45° and a width of 100 (Figure 6).

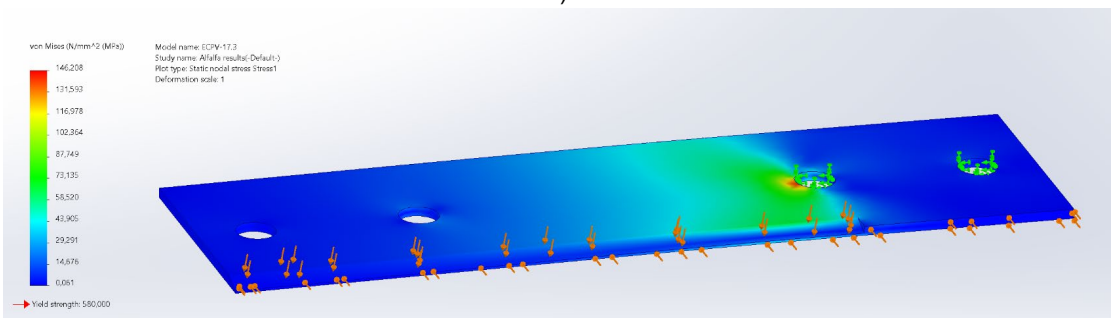
Component name	Units	Current	Initial	Optimal	Scenario1	Scenario2
A	mm	50	50	100	50	100
B	deg	30°	30°	45°	30°	30°
C	mm	4	4	4	4	4
D	mm	240	240	360	240	240
E	N/A	0.25	0.25	0.75	0.25	0.25
Minimum Factor of Safety1		3.894586	3.894586	3.966846	3.740210	4.978802
Mass1	kg	0.34169	0.34169	1.0664	0.34242	0.71682
Minimum Factor of Safety2		3.894586	3.894586	3.966846	3.740210	4.978802

Fig. 6 - Design study results for the blade model during alfalfa cutting

The results shown above represent significant improvements, lowering the factor of safety by 89,47%, from 38 to a 3.967 value, the weight of our blade was lowered by 39% down to 1.07 Kg allowing us to cut down the costs of manufacturing the blade by 39.2%. To assess the structural performance of the updated design, the earlier simulations were repeated, focusing on the resulting deformation (Figure 7a) and stress distribution on the blade (Figure 7b).



a)



b)

Fig. 7 - Simulation results on the newly updated design

To further evaluate the structural performance of the optimized blade design, previous simulation setup was used to represent the cutting of thicker grass, which introduces greater resistance and load on the cutting edge. This analysis aimed to verify whether the updated design could maintain structural integrity under more demanding operating conditions.

However, the results revealed a significant issue: the Factor of Safety (FOS) decreased to 0.5, a value considerably below the acceptable threshold for safe operation. With such a low FOS indicating a high risk of structural failure under realistic field conditions, it was decided to perform the Design Study once more, this time based on the simulation results of the thicker grass scenario, in order to obtain a safer and more reliable configuration.

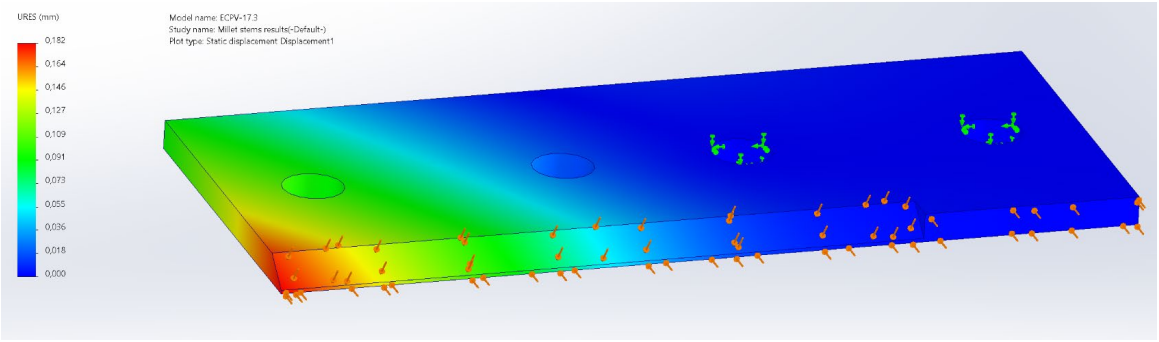
As a result of this new optimization process, we achieved a blade design characterized by the following parameters: a blade thickness of 8 mm, a total length of 240 mm with a cutting edge of 75 % of the total length, a cutting angle of 45°, and a width of 100 mm (Figure 8).

Component name	Units	Current	Initial	Optimal	Scenario1	Scenario2
A	mm	100	100	100	50	100
B	deg	45°	45°	45°	30°	30°
C	mm	4	4	8	4	4
D	mm	360	360	240	240	240
E	N/A	0.75	0.75	0.75	0.25	0.25
Minimum Factor of Safety1		4.966	3.966846	3.922	3.740210	4.978802
Mass1	kg	1.06 kg	1.0664	1.4	0.34242	0.71682
Minimum Factor of Safety2		4.966	3.966846	3.922	3.740210	4.978802

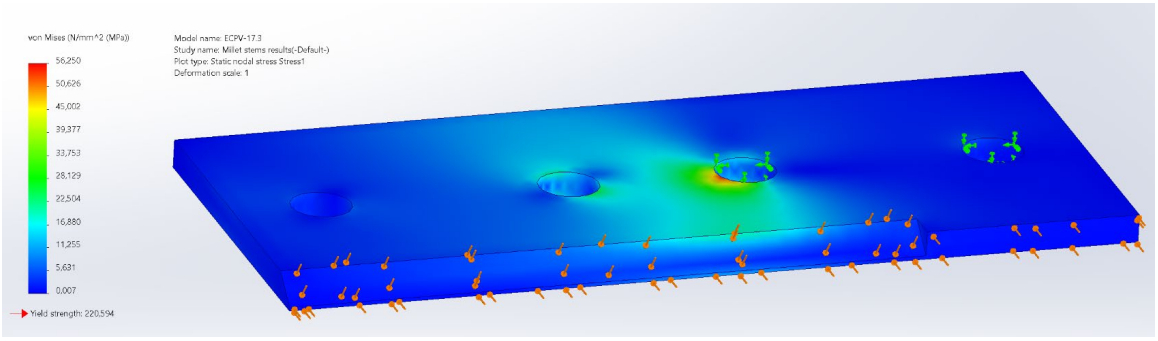
Fig. 8 - Design study results for the blade model during millet stems cutting

The results obtained show a clear improvement, increasing the Factor of Safety from 0.5 to 3.9. To assess the structural performance of this updated design, the simulations were repeated, focusing on the resulting deformation (Figure 9a) and stress distribution on the blade (Figure 9b).

These results clearly demonstrate the effectiveness of the Design Study in optimizing the blade's geometry, improving its structural reliability, and achieving a more efficient and cost-effective configuration suitable for varying cutting conditions.



a)



b)

Fig. 9 - Simulation results on the final designed blade

CONCLUSIONS

The study demonstrated that systematic use of SolidWorks Simulation and the Design Study module can significantly enhance the structural performance of the cutting blades for a mowing equipment. By iteratively refining geometric parameters such as thickness, length, cutting angle, and width, the optimized blade achieved a substantial improvement by lowering the Factor of Safety, from 38 to 3.9, while also reducing mass and manufacturing costs. These results confirm the value of simulation-based design as an efficient and reliable method for optimizing agricultural machinery components. Furthermore, integrating real operating conditions into the simulation process ensures that the resulting design maintains durability, efficiency, and cost-effectiveness when exposed to varying vegetation densities and cutting environments.

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BIOCHAR IN SUSTAINABLE AGRICULTURE: EFFECTIVE APPLICATION STRATEGIES FOR SOIL IMPROVEMENT AND PRODUCTIVITY INCREASE- REVIEW

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BIOCHARUL ÎN AGRICULTURA DURABILĂ: STRATEGII EFICIENTE DE APLICARE PENTRU ÎMBUNĂTĂȚIREA SOLULUI ȘI CREȘTEREA PRODUCTIVITĂȚII - REVIEW

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Keywords: *biochar, soil amendment, soil fertility, soil structure, sustainable development, climate change*

ABSTRACT

The following material analyzes the potential of biochar as a sustainable agricultural amendment, with a focus on how its application influences soil fertility, crop productivity, and agroecological processes. The study explores key aspects such as timing of application, incorporation depth, dosage, type of biochar, as well as the technologies used for its integration into the soil. The paper synthesizes recent experimental results that highlight the effectiveness of composted biochar compared to other forms of application, demonstrating its positive impact on soil pH, microbial activity, and plant yield. It emphasizes the need for adopting biochar as an integral part of a sustainable agricultural system adapted to local conditions, underlining the importance of applied research and institutional support for large-scale implementation.

REZUMAT

In materialul de mai jos este analizat potențialul biocharului ca amendament agricol sustenabil, cu accent pe modul în care aplicarea sa influențează fertilitatea solului, productivitatea culturilor și procesele agroecologice. Sunt dezvoltate aspecte legate de momentul aplicării, adâncimea, cantitatea, tipul de biochar, precum și tehnologiile utilizate pentru încorporare. Lucrarea sintetizează rezultate experimentale recente care indică eficiența biocharului compostat comparativ cu alte forme de aplicare, demonstrând impactul pozitiv asupra pH-ului solului, activității microbiene și randamentului plantelor. Se subliniază nevoia adoptării biocharului ca parte integrantă a unui sistem agricol durabil și adaptat condițiilor locale, subliniind importanța cercetării aplicate și a sprijinului instituțional pentru implementare la scară largă.

INTRODUCTION

In the context of the climate crisis and the depletion of natural resources, modern agriculture is facing increasing pressure to become more sustainable, productive, and resilient. Soil degradation, biodiversity loss, and crop yield volatility (*Chen et al., 2024*) demand the development of innovative solutions. Biochar – a stable, carbon-rich material obtained through the pyrolysis of biomass (*Bruun et al., 2012*) under limited oxygen conditions – is being promoted as a viable option for soil regeneration and reducing agriculture's carbon footprint.

Its physico-chemical properties, such as porosity, water retention capacity, alkaline pH, and recalcitrant carbon content, make it a valuable ally in strategies aimed at improving soil quality. However, the effectiveness of biochar depends on numerous factors: soil type, crop species, climate conditions, feedstock used, and especially the technology and timing of application. This paper explores all these dimensions, offering an up-to-date synthesis of scientific literature and recent experimental data.

Biochar, produced through biomass pyrolysis under reduced oxygen conditions, offers multiple benefits for agriculture and the environment. Due to its porous structure, it retains water and nutrients, enhances soil fertility and structure *(Singh et al., 2023)*, increases pH, reduces greenhouse gas emissions (*Li et al., 2024*), and mitigates heavy metal pollution. It is particularly effective in restoring degraded soils, especially in arid regions or areas with poor-quality soils.

Applying biochar increases crop yields *(Huang et al., 2023*), improves nutrient retention, supports microbial activity, and reduces the need for chemical fertilizers (Wang et al., 2024). It is successfully used in

greenhouses, gardens, agriculture, forestry, construction, and even in water filtration or as a feed additive. An additional advantage is the production of clean energy during the pyrolysis process.

Although the use of biochar may seem like a recent innovation, the technique has been used for thousands of years. Today, biochar is recognized as a key tool for regenerative agriculture and climate change mitigation *(Kumar et al., 2025)*, through carbon sequestration and the reduction of CO_2, CH_4, and N_2O emissions.

The success of thermochemical conversion technologies and biochar adoption depends on local conditions, biomass availability, and market demand. In this context, biochar becomes a key element in the circular economy, transforming organic waste (*Zhao et al., 2025*) into a valuable resource with positive economic and ecological impacts.(*https://www.businessagricol.ro/biocharul-parte-a-economiei-circulare-solutie-ideala-de-transformare-a-deseurilor-organice/*)

To fully harness the potential of biochar, it must be integrated into a set of sustainable agricultural practices. In a circular farming system, biochar can be effectively combined with compost or organic fertilizers (*Schmidt et al., 2021*), contributing to improved soil structure and increased water-holding capacity. In Romania, some farmers have already begun applying these integrated solutions, using biochar alongside crop rotation and cover crops, which helps prevent erosion, soil-borne diseases, and supports long-term soil fertility.

Collaboration between researchers, farmers, and authorities is essential for the effective adaptation of biochar use (*Sohi et al., 2010*) under various agricultural conditions. At the European level, biochar has been successfully integrated into organic farms, contributing to increased yields (*Biederman & Harpole, 2013*) and reduced greenhouse gas emissions. Institutional support, in the form of financial incentives, can accelerate the adoption of this innovative technology, strengthening the transition toward sustainable practices.

Thus, biochar represents a promising solution for enhancing food security, protecting natural resources, and combating the effects of climate change. Its widespread adoption could drive the development of regenerative, sustainable agriculture that is adapted to current challenges. For effective implementation, it is recommended to consult environmental specialists who can assist with obtaining the necessary permits and ensuring compliance with environmental regulations.(*https://stratos.ro/blog-biochar-sau-carbunele-vegetal-un-produs-ideal-pentru-practicile-agricole-sustenabile/*)

Fig.1 - Characteristics of biochar
https://www.bestongroup.com/ro/biochar-production-equipment/amp/

The most important characteristics of biochar are (Fig 1):

a) Porous structure:

Biochar has a dense network of micropores both on the surface and within its internal matrix. This porous structure provides a high specific surface area, typically ranging between 200 and 500 m²/g. Thanks to this feature, biochar exhibits excellent adsorption capacity and effectively contributes to water and nutrient retention in the soil.

b) Rich content of functional groups:

The surface of biochar is covered with various functional groups, such as hydroxyl and carboxyl. These offer multiple active sites for chemical interactions with minerals, microorganisms, or organic matter, thereby enhancing biochar's ability to adsorb beneficial substances.

c) Remarkable stability and durability:

The carbon in biochar is primarily present in stable aromatic forms, giving it high chemical and thermal resistance. Due to this stability, biochar degrades very slowly in the environment and can remain active in the soil for hundreds of years.

Biochar is a carbon-rich material obtained through the pyrolysis of biomass, such as wood, agricultural waste, or other plant residues. Biochar production equipment ensures that the pyrolysis process takes place at high temperatures and in the absence of oxygen. This production method gives biochar a series of distinct properties:

MATERIALS AND METHODS

In general, biochar can be applied to soil through several methods, each with specific characteristics and benefits. One of the simplest approaches is direct application, where biochar is spread on the soil and mechanically incorporated. However, the effectiveness of this method can vary depending on soil type and the crop to be planted. A frequently used alternative is mixing biochar with mature compost (*Agegnehu et al., 2016*), which allows for better homogenization and distribution of nutrients. However, the most effective method, according to recent studies, is composting biochar—a complex biological process in which biochar is integrated into a mix of organic materials (plant residues, manure, green waste, etc.) and subjected to controlled fermentation. In this context, biochar not only acts as a physical support for microbial colonies (*Liu et al., 2024*), but also actively participates in the transformation of organic matter. This interaction enhances humification and mineralization processes, helps stabilize pH, reduces phytotoxic compounds, and increases the accumulation of available nutrients (nitrogen, phosphorus, potassium). Composting also improves the water and nutrient retention capacity of biochar, increasing its efficiency in the soil and ensuring a slow, sustained release of nutrients needed by plants. Thus, composted biochar becomes a complex soil amendment (*Zhang et al., 2025*) with higher agronomic value than other application forms.

The application of biochar to soil is closely linked to the stages of agricultural land preparation, since the efficiency of this amendment largely depends on proper integration into the active soil profile. The most suitable periods for application are autumn, immediately after harvest, and spring, before sowing, as these are the typical times for basic mechanical works such as plowing, disking, or rotary tilling, which allow for deep and uniform incorporation of the material.

Autumn application offers several advantages. After harvest, the soil remains bare until the next crop cycle, providing a time window in which biochar can be applied without interfering with plants. Moreover, biochar has time to interact with the soil and undergo an “activation” process—that is, the absorption of nutrients and colonization by beneficial microorganisms—before the next growing season begins. This “maturation” period in the soil enhances the efficiency of biochar in improving soil structure, water retention, and nutrient availability.

Spring application, before sowing, is also a viable option, especially when a rapid response is desired during the growing season. In this case, it is important for the biochar to be well incorporated before the crop is established to avoid losses through wind or overexposure to sunlight, as well as to prevent possible temporary nutrient lock-up (the so-called “initial adsorption effect”). Therefore, combining biochar with compost or natural fertilizers is often recommended, particularly in spring.

In both cases, synchronizing biochar application with already planned mechanical operations reduces additional costs and minimizes soil disturbance. Thus, biochar becomes an integral part of the agricultural system, contributing sustainably to the long-term improvement of soil fertility.

The amount of biochar applied depends on several factors, including soil type, crop needs, current soil condition, and agronomic goals. Typically, the quantity is expressed in tons of biochar per hectare (t/ha), and recommendations vary between 5 and 20 t/ha depending on each specific situation.

Optimal quantity for carbon-poor soils

In soils with low organic matter or degraded conditions, an application of 10–20 t/ha of biochar is recommended. This helps improve soil structure, increase water retention and aeration, and support the development of beneficial microorganisms. Carbon-poor soils benefit the most from biochar, as it provides stable carbon that remains available long-term.

If the soil is already fertile and well-balanced in terms of organic matter, the amount of biochar can be reduced to 5–10 t/ha. Application at this rate will contribute more to nutrient stabilization and soil structure improvement without risking carbon oversaturation. In such cases, biochar can be used primarily as an amendment to enhance water retention and optimize nutrient availability during drought periods.

In some situations, biochar can be applied in combination with other soil amendments such as compost or organic fertilizers. These combinations enhance the benefits of biochar by increasing nutrient availability and supporting soil microbiology. For example, a combined application of 5–10 t/ha of biochar and 20–30 t/ha of compost can be effective in boosting microbial activity and improving soil structure.

It is important to monitor the impact of biochar application on soil and crops to adjust the amount based on the results. For instance, if biochar effects are visible within one year but not sufficiently strong, the amount can be increased in subsequent years. On the other hand, if the soil becomes too rich in carbon or if nutrient imbalances occur, future applications can be reduced.

The depth at which biochar is applied is a key factor that directly influences its efficiency in the soil. To obtain maximum benefits, biochar must be incorporated into the active soil layer, where biological activity is highest and plant roots develop most effectively. Generally, this zone corresponds to the top 10–30 cm of soil, depending on the crop type and farming system used.

For annual crops (wheat, corn, (*Wijitkosum et al., 2025*), soybeans, etc.), the optimal incorporation depth is 15–25 cm, as the roots of these plants mainly develop in the upper layer. Incorporation at this depth allows biochar to improve soil structure, increase water retention, and regulate nutrient availability precisely where plants need it.

For perennial crops or fruit trees, a deeper or localized application around the root zone is recommended—down to 30–40 cm—to directly influence the mature root absorption area. In such cases, biochar can be introduced either through pits or fertilization bands.

Too shallow an application (0–5 cm) may lead to wind erosion losses, especially in light soils or arid zones, and reduces contact with soil microorganisms. Conversely, incorporation that is too deep (>40 cm) may reduce effectiveness, as the biochar no longer interacts efficiently with plant roots and the biologically active layer.

Modern application techniques, such as plowing, rotary tilling, or strip tillage, enable precise and uniform incorporation of biochar at the desired depth. This ensures optimal distribution and effective interaction between biochar, soil, and plants.

Particle size and feedstock type are essential factors influencing the interaction of biochar with soil and plants, determining its efficiency and long-term benefits. In terms of particle size, this affects the dynamics of biochemical and physical reactions in the soil. Fine biochar (under 2 mm) has a large specific surface area, meaning higher chemical reactivity. It promotes fast biochemical reactions, improves microbial activity in the soil, and has a significant impact on nutrient availability and water retention. Due to its smaller particles, fine biochar may be more effective in stimulating biological activity and enhancing the soil's capacity to support microbial life.

In contrast, coarse biochar (2–10 mm) offers greater porosity, contributing to the improvement of physical soil structure (Glaser et al., 2002). It is not as chemically reactive but helps improve soil aeration and prevent compaction. Thanks to its larger particle size, coarse biochar provides longer durability in soil, being more stable over time, and can be useful in areas where maintaining a stable soil structure long-term is desired.

The type of feedstock used to produce biochar also influences its physico-chemical properties, stability, and biodegradability. Biochar made from hardwood (such as beech or oak) is chemically more stable and has higher durability in the soil, as it decomposes much more slowly than other types of biochar. This makes it ideal for long-term soil structure improvement and carbon stabilization in the soil, providing lasting impact. Hardwood biochar is low in nutrients at production but contributes to improved physical structure and soil stability, often used in organic farming where long-term stability is essential.

On the other hand, biochar made from plant residues (such as straw or corn stover) is richer in nutrients and more biodegradable. It decomposes faster in the soil, meaning it supplies nutrients more quickly and supports rapid plant growth. Plant-residue biochar significantly contributes to microbial activity

and improves nutrient availability for plants, although it has lower durability than hardwood biochar. This type is useful in soils requiring a quick nutrient supply and where an immediate impact on soil fertility is desired.

Choosing between fine or coarse biochar, and between hardwood or plant-residue biochar, depends on agronomic goals, soil type, and crop needs. Combining these characteristics can optimize the benefits of biochar according to the specific conditions of each farm.

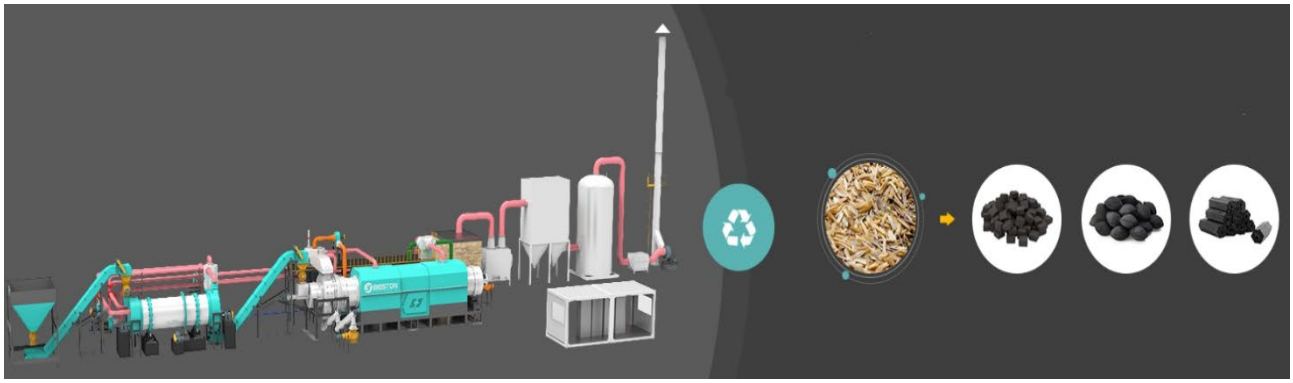

Fig. 2 - Rice husk biochar production machine

(https://www.bestongroup.com/ro/charcoal-making-machine/rice-husk/)

The rice husk carbonization machine (Fig. 2) provides an efficient and sustainable solution for the valorization of agricultural biomass waste. Over time, the rice industry has faced challenges regarding the optimal use of rice husks. Today, thanks to carbonization technology, these plant residues can be transformed into biochar, a valuable product with multiple uses. Thus, the process not only increases the economic value of this agricultural by-product but also opens up new income opportunities for the rice industry while supporting sustainable farming practices.

Sawdust biochar production machine

The sawdust biochar production machine converts sawdust into high-quality charcoal through pyrolysis technology. It offers an efficient solution for waste disposal in the wood processing industry. This sawdust charcoal has wide applications in industry, agriculture, and other sectors, presenting profitable prospects for investors.

Wood biochar production machine

The wood biochar production machine provides an effective solution for the disposal of wood waste generated by the forestry and wood processing industries. Using high-temperature pyrolysis technology under low-oxygen conditions, it transforms wood residues into high-value charcoal. The entire process is environmentally friendly, ensuring minimal environmental impact. There is also the coconut shell charcoal machine, an efficient solution for recycling coconut shell waste.

Fig. 3 - Palm kernel shell biochar production machine

(https://www.bestongroup.com/ro/charcoal-making-machine/palm-kernel-shell/)

The palm kernel shell biochar production machine is gaining increasing popularity in the market (Fig.3). Using pyrolysis technology, this equipment efficiently transforms palm kernel shells into high-value

charcoal. Due to the high demand and multiple uses of this type of charcoal, investing in such equipment can bring considerable profits.

Fig. 4 - Bamboo biochar production machine
(https://www.bestongroup.com/ro/charcoal-making-machine/bamboo/)

The Beston bamboo charcoal production machine efficiently transforms bamboo into valuable charcoal (Fig. 4). Similar to that obtained from wood or coconut shells, bamboo charcoal has multiple uses and a considerable market value.

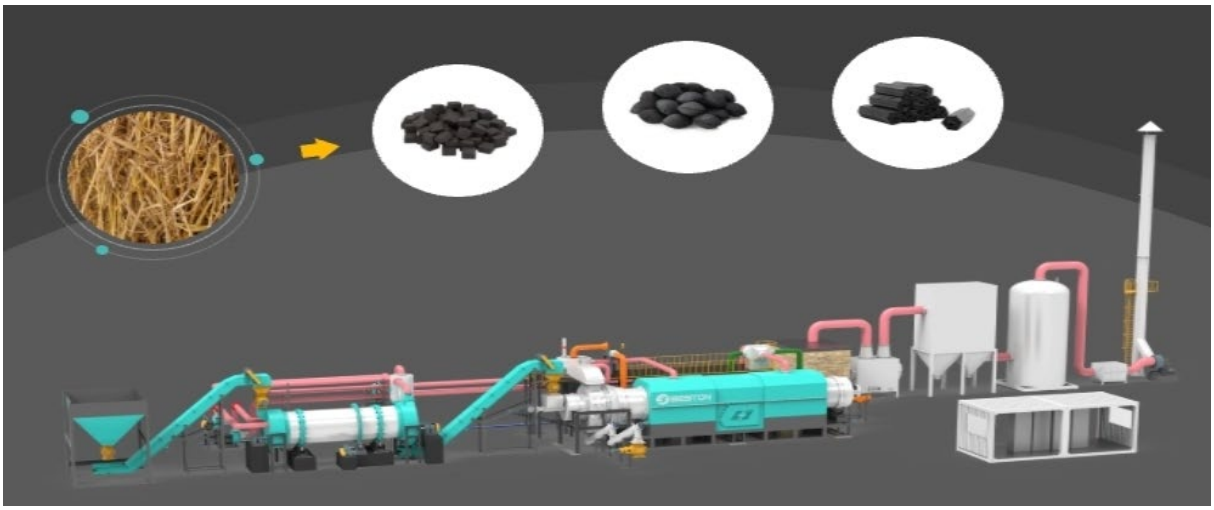

Fig. 5 - Straw biochar production machine
(https://www.bestongroup.com/ro/charcoal-making-machine/straw/amp/)

The straw charcoal production machine is designed to convert agricultural waste, such as straw, into valuable biochar using pyrolysis technology (Fig. 5). This equipment represents an efficient solution for the sustainable management of waste and resource utilization, bringing both economic advantages and environmental benefits. Continue reading to discover the main features of this straw charcoal production machine.

Application Technologies:

Efficient application of biochar to the soil requires the use of adapted equipment to ensure uniform distribution, proper incorporation, and integration into the active soil profile. The choice of the right technology depends on the form of the biochar (granulation, moisture), the type of crop, the soil texture, and the timing of application. In practice, a range of modern agricultural machinery is used, as follows:

1 Solid Fertilizer Distributors: These machines are essential for the uniform distribution of biochar over the land surface. They can be tractor-mounted or self-propelled and are adjustable depending on the desired amount (5–20 t/ha). Modern distributors allow for flow regulation and controlled coverage of areas, reducing losses and ensuring homogeneous application. They are particularly effective in the pre-application phase, before mechanical incorporation.

2 Disc Harrows and Rotary Tillers: After application, biochar must be incorporated into the soil to prevent losses due to wind or leaching. Disc harrows or rotary tillers are used for shallow mixing (10–20 cm), promoting contact with the rhizosphere. Rotary tillers are especially useful in light soils or sensitive crops, where fine and uniform tillage is required.

3 Multifunctional Seeders (Double Reservoir Seeders or "Strip-Till" Systems): In modern agricultural technologies, some seeders are equipped with double reservoirs that allow simultaneous application of seeds and biochar, either in bands (banding) or at row level. This system optimizes space and resources, ensuring localized application closer to the plant's area of interest. These machines are particularly useful in precision farming and conservation systems.

4 Subsoilers and Plows for Deep Tillage: In compacted or poorly developed soils, deep soil preparation is required. Subsoilers allow loosening at depths of 30–40 cm, promoting the penetration of biochar and water, as well as root development across an extended profile. Classic plows (for autumn plowing) ensure the turning of the furrow and are useful for integrating biochar into deeper soil layers, providing good results in traditional agricultural systems.

The choice of application technology should align with the agronomic goal, type of biochar, and pedoclimatic conditions. Integrating these technologies into a sustainable fertilization plan helps maximize the benefits of biochar and increase long-term yield.

RESULTS

The type of raw material used to produce biochar not only influences its physical and chemical characteristics but also its durability, stability, and nutritional composition. Biochar can be produced from a variety of sources, including wood, plant residues, or even organic waste, and each type has its specific advantages and characteristics:

Hardwood Biochar (beech, oak, etc.)

Biochar produced from hardwood is characterized by higher chemical stability and greater durability in the soil. It decomposes much more slowly than biochar derived from more easily biodegradable plant sources, making it ideal for improving soil structure in the long term. Hardwood biochar is nutrient-depleted during production but can be useful in soils that do not require a large amount of additional nutrients, being particularly effective in stabilizing carbon in the soil. This type of biochar is preferred in organic farming, where long-term stability is a priority.

Biochar from Plant Residues (straw, corn residues, grass, etc.)

Unlike hardwood biochar, biochar derived from plant residues is generally richer in nutrients, often being a valuable source of nitrogen, phosphorus, and potassium. This biochar is more biodegradable, with a shorter decomposition time in the soil, and can significantly contribute to nutrient supply for plants, especially in the early growth stages. It is ideal for soils that need additional nutrient supplementation and for applications where rapid replenishment of nutrient reserves is desired. Additionally, plant residue biochar helps improve microbial activity and soil structure, but with lower durability compared to hardwood biochar.

Choosing the Right Biochar Type Based on Soil and Crop Needs

For efficient use of biochar, the selection of raw material type and granulation should be made based on the soil characteristics and the specific requirements of the crop. For example, in soils that require long-term improvement of physical structure and high stability, hardwood biochar with coarse granulation may be the most suitable choice. On the other hand, for soils that benefit from rapid fertilization and quick plant growth, plant residue biochar with fine granulation may be the ideal option.

The use of biochar in agriculture has demonstrated clear benefits for soil fertility and plant development, according to an increasing number of experimental studies. In a study conducted on Luvisol and Fluvisol soils, the application of biochar led to significant increases in the biomass of lettuce plants. It was observed that when biochar was integrated into the soil together with compost, whether pre-composted or not, the effects were clearly positive: biomass increased up to six times in some variants. This development clearly highlights the potential of biochar to support plant productivity (Jeffery et al., 2011), and combinations with other organic amendments can amplify results, without its effectiveness depending solely on additional pre-treatments.

Another consistent result observed in biochar applications is the increase in soil pH values. This effect is particularly valuable in acidic soils, where biochar helps reduce acidity and improve nutrient absorption conditions for plants. Along with this change in soil pH, better mobilization of macro- and

micronutrients, such as phosphorus, potassium, or calcium, has been noted, leading to a more favorable environment for plant growth.

Additionally, the dissolved organic carbon and total nitrogen content increased significantly in soils amended with biochar, indicating an improvement in the natural cycles of organic matter and better biological functioning of the soil. These effects are particularly important in degraded or nutrient-poor soils, where biochar can act as a catalyst for regeneration. By retaining nutrients and providing a stable, porous structure, biochar supports microbial activity and helps form a balanced trophic network in the soil.

Interaction with soil organisms is another crucial aspect. It has been observed that biochar stimulates the activity of microorganisms involved in essential processes such as atmospheric nitrogen fixation, organic matter decomposition, or the formation of stable soil aggregates. By providing a protective and stable physical habitat, biochar supports microbial biodiversity and, implicitly, the efficient functioning of the soil ecosystem.

The results support the idea that biochar, as an organic amendment with unique properties, brings significant improvements to soil structure, chemical composition, and biological activity. These effects are visible both in intensive farming contexts and in ecological restoration systems, especially in soils with low fertility or under stress. Therefore, biochar proves to be a valuable tool for the sustainable increase in agricultural productivity and for restoring the natural capacity of soils to support plant life.

Optimal application dose:

$$D = (K \times (1 + Fs)) / T \quad (1)$$

where:

D = recommended dose (t/ha)

K = amendment coefficient (generally between 10–20)

Fs = soil fertility factor (0 – fertile soil; 1 – poor soil)

T = texture index (1 for sandy, 2 for loamy, 3 for clayey)

For a clearer understanding of how biochar can be applied to soil, two relevant tables are presented below:

Table 1 provides a comparison of the main biochar application methods, highlighting the advantages and disadvantages of each option. Table 2 presents the recommended biochar application rates, depending on crop type and soil texture, in order to maximize its effectiveness.

Table 1

Comparison of biochar application methods

Application Method	Main Advantages	Disadvantages	Estimated Efficiency (%)
Simple Biochar	Easy to apply, stable material	Slow impact, risk of phytotoxicity	40–60%
Mixed with Compost	Easy to apply, nutrient supply	Limited microbial activity	60–80%
Composted Biochar	High biological activity, pH balance	Requires time and space for composting	80–95%

Table 2

Recommended biochar dose based on crop and soil texture

Crop	Soil Texture	Recommended Granulation	Dose (t/ha)	Application Period
Wheat	Loamy	< 2 mm	10–15	Autumn
Corn	Clayey	< 2 mm	15–20	Spring
Grapevine	Loamy-clayey	2–10 mm	5–10	Autumn
Vegetables (various)	Sandy	< 2 mm	10–20	Spring

CONCLUSIONS

The application of biochar to soil represents a promising strategy for sustainable agriculture, especially in the current context of climate change and depletion of natural resources. Its versatility, combined with the proven effectiveness of the composted form, provides a valuable alternative to traditional amendments. To maximize the benefits, it is essential to adapt the application technique to the local specifics: soil texture, crop type, available equipment, and climatic conditions. Additionally, integrating biochar into good agricultural practices, supported by public policies, subsidies, and farmer

training programs, is crucial. Biochar can become a key factor in the transition to a circular, ecological, and resilient agriculture capable of meeting the challenges of the future.

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ANALYSIS OF INTERNATIONAL STANDARDS THAT CERTIFAY THE PRODUCTS QUALITY OF PYROLYSIS PROCESS- REVIEW

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ANALIZA STANDARDELOR INTERNAȚIONALE CARE CERTIFICA CALITATEA PRODUSELOR OBȚINUTE DIN PROCESUL DE PIROLIZĂ

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ABSTRACT

In this paper, are presented some international merchet regulation concerning the bio-char quality certification, so the buyer to have all the necessary information's to apply in safety the pyrolysis products according to: crop type (vegetables, horticulture, pomiculture, etc.); the food category resulted (ecologic, bio, chemical treated, etc.), soil quality, costs, sustainability, conversion, etc. Taking in to consideration, the grate number of pyrolysis technologies on market, the variety of the installations studied in scientific literature that obtain bio-char from a large category of by-products and organic wastes (straw, sawdust, farm manure, food industry waste, etc.), it is necessary that the material obtained to be compliance with quality standards or regulations, so that the buyer/user/reader to have all the correct information's so to be able to adopt the correct technology for the crop and environmental factors and streamline production costs. An important direction in agricultural scientific literature the study of biochar-based fertilizers is known as Slow-Release Fertilizers (SRFs), and is seen as an effective and ecologically approach to advancing sustainable agriculture. Nowadays, experimental fields are established to prove and develop adaptive efficient technology, in accordance with soil and environmental specifications, to improved crop growth and quality.

REZUMAT

În această lucrare se prezintă câteva reglementări ale pieței internaționale privind certificarea bio-cărbunelui de calitate, astfel încât cumpărătorul să aibă toate informațiile necesare pentru a aplica produsele din procesele de piroliză în siguranță și în conformitate cu: tipul culturii (legumicole, floricole, pomicole, etc.); de categoria produselor alimentare rezultate (ecologică, bio, conversie sau tratate chimic) și de calitatea solului, etc. Având în vedere faptul că, există pe piață un număr important de instalațiile de piroliză prezente pe piață, iar în literatura de specialitate sunt studiate variate care produc bio-cărbune din diferite materii secundare sau deșeuri organice (paie, rumeguș, dejecții din ferme, deșeuri din industria alimentară, etc.), este necesar ca materialul obținut să fie în conformitate cu standarde sau reglementări de calitate, pentru ca cumpărătorul/utilizatorul/cititorul să amibe toate datele pentru foi capabil să adopte tehnologia corecta la cultura si al factorii de mediu si sa eficientizeze costurile de producție. O direcție importantă în literatura științifică agricolă o reprezintă fertilizanții bio-cărbune, cunoscuți ca fertilizanți lenți (SRF), care reprezintă o abordare eficienta si ecologica către agricultura sustenabilă. Actualmente, câmpuri experimentale sunt înființate pentru a dovedi și dezvolta tehnologi eficiente si adaptive, la condițiile de sol si de mediu, pentru a crește dezvoltarea si calitatea culturilor.

INTRODUCTION

Scientists from agriculture and soil nutritional improvement, are working to determine some dedicated administration of SRFs technologies to achieve slow release. During research activities it was observed it is a limited available literature on biochar-based SRFs and nano SRFs. More then this the bio-char sample preparation, analysis methodology and test result are made using different devices, measurement equipment's and without mentioning the methodology used.

So, doing so, the results are difficult to replicate and hard to integrate in a dedicated sustainable agriculture technology. For this reason, was needed to implement standards and specific regulations as: Word Certification and International Carbon Standards, European Union (EN), and China standard (GB), have collectively classified these types of fertilizers as SRFs. *(Divyangkumar N., Panwar N.L, 2024).*

The certification system influences the commercial value and utilization of biochar, are set in standards set and guidelines by the European Biochar Certificate Standard (EBC-version 10.5E), World Biochar Certificate (WBC-version 1.1), International Biochar Initiative (IBI), and the Biochar Quality Mandate (BQM) (*Camps-Arbestain, M., Amonette, J.E., Singh, B.,2015, H.-P. Schmidt, 2012)* an intuitive diagram is presented by (*Liu Q., Meki K.,. Zheng H, et. Al, 2022*).

Furthermore, same of the EU patterns, such as: Germany, China, Switzerland, Austria, and Italy, have incorporated biochar into their respective national regulations concerning fertilizers, soil additives, and composts (*Meyer, S., Genesio, L., Vogel, I., et al, 2017*).

Also, Romania has some regulations regarding fertilizer administration but, this documentation must by applied cheerfully in accordance with field agroclimatic specifications and crop needs, so to protect the near fauna and flora, but also to prevent unpredictable environmental damage.

1. ***The International Biochar Initiative (IBI)*** has the main role to established guidelines and standards, in which are define dedicated testing procedures to produce biochar. The aim is to provide stakeholders and commercial entities, a clear framework to identifying biochar's specific qualities and properties. Also, aims to implement the IBI Biochar Certification Program so needed for biochar producers. A large category of byproducts and vegetal /animal waste are considerate feedstocks through diverse thermochemical conversion processes, resulting in various characteristics, only those that have more than 10 % (w%) of organic carbon (C_{org}). These standards classify biochar materials into three main properties: part A - tests for fundamental functional properties (mandatory for all biochar); part B – tests for toxicant evaluation; and part C - test for advanced evaluation and soil improvement properties. The latest version 10.5E of the IBI, include also a part for pyrolysis heat recovery that is suggested to be used to dray the feedstock or as a radiant heating agent in industrial hall of homes in vicinity, that part was necessary to be added in order to improve pyrolysis energetic balance. Another important part is to reintroduce slow pyrolysis generation gases in the reactor, after were extracted the humidity and tar fraction. Consulting the feedstock source table, we so that the poultry litter, is mentioned as a high environmental pollution source, so the handling installations and operators must comply with complex regulation, especially regarding the breading masks.

2. ***The European Biochar Certificate EBC*** are optional industrial standard in Europe and Switzerland however, it is compulsory for the utilization of biochar in agriculture. In this document the Biochar is categorizes into six classes: "Feed", "Agro-Organic", "Agro", "Urban", "Consumer Materials", and "Basic Materials". The EBC guidelines specific that, a biochar must have a C_{org} content of more than 50% (w%). In Annexes are ISO and regional regulation listed methods as: ISO 13909-4 and DIN 51701-3 - for sample preparation; DIN EN ISO 17828- bulk density; DIN ISO 11265- salinity; DIN ISO 10390- pH evaluation; ISO 589 and DIN 51718 - humidity; ISO 1171 and DIN 51719 – ash content 550 °C; ISO 925 and DIN 51726 – carbonate CO_2; ISO 29541 and DIN 51732 – CHN content; ISO 19579 and DIN 51724-3 – Sulphur content; ISO 17247 and DIN 51733 – Oxygen content; DIN EN 17503 – PAH content; EN ISO 12846, DIN 22022-1, DIN 22022-7, DIN EN ISO 17294-2 / DIN EN 1483 - trace metals after microwave-assisted digestion (Pb, Cd, Cu, Ni, Hg, Zn, Cr, B, Mn, As, Ag); ISO 23380, DIN 51729-11, DIN EN ISO 11885 / DIN EN ISO 17294-2 – nutrient content (P, Mg, Ca, K, Na, Fe, Si, S); DIN EN ISO 14238 – water holding capacity; DIN EN 15763- trace metals (As, Pb, Cd, Hg); etc. An important, for our research domain is that poultry litter is not mentioned, and can be integrated in “Animal by-products feedstock” (AB02) or “other animal by-products” (AB03), from the legal point of view in bought categories, the feedstock must have passed an end-point according to Commission Delegated Regulation (EC) 2023/1605.

An older British standard/Dansk Standard/European Standard (DS/EN 13266:2001) which is referring to “Slow-release fertilizers-Determination of the release of the nutrients-Method for coated fertilizer” (2001), was adopted by British Standard (BS confirmed in 2011) - It is focuses on coated SRFs, another technological trend based on the biochar structure and capacity. So, a SRF must comply the next requirements: 1) > 15 % of a nutrient released in 24 h; 2) > 75 % of a nutrient released in 28 days; 3) at least 75 % of a nutrient released at the stated release time. (*Duan, Q., Jiang, S., Chen, F., et all., 2023*)

3. The BS ISO 19670:2017 promulgated the Fertilizer and soil conditioners-Solid urea aldehyde slow-release fertilizer-General requirements." – this document is dedicated solubility urea-based fertilizers, because in bought cases present limited nitrogen nutrients (terms defined: urea aldehyde slow-release fertilizer; cold water insoluble and soluble nitrogen; hot water insoluble and soluble nitrogen). The standard requirements presented in this standard are: (1) visual inspection (shall be in powder, granules, prills, pellets, pastilles, chips, or other solid forms); (2) nitrogen content in the urea-based SRF (total nitrogen > 28% and 36 % formaldehyde/methylene and IBDU/CDU urea fertilizer respectively). The base term was prior defined in ISO 8157:2015, Fertilizers and soil conditioners — Vocabulary. The standard also detail describes the sample preparation and measurement methods. Also, in 2017 was promulgated BS ISO 21263:2017 "Slow-release fertilizers-Determination of the release of the nutrients-Method for coated fertilizers." (*Duan, Q., Jiang, S., Chen, F., et all., 2023*).

4. The Chinese government recently introduced a standard for complex compound fertilizers GB 15063–2001 revised in 2009, and after that supersede by GB/T 15063-2020 Compound fertilizer. As in the other standards here are presented, dedicated terms and complex fertilizers definitions, bulk blending fertilizer, organic-inorganic com-pound fertilizer, primary nutrients, the second element, trace elements, and formula. Requirements of the Standard include: 1 - visual inspection (powder, granules, prills, pellets, pastilles, chips, or other solid forms without any hard particles); 2 - nitrogen content in the urea-based SRF, classified as three grades: high concentration (total nutrients > 40), medium concentration (total nutrients > 30), and low concentration (total nutrients > 25); 3 - particle size is between 1.00 and 4.75 mm; 4- moisture content for high, medium and low concentration samples are < 2.0 %, 2.5 % and 4.0 % respectively. More than this, the Chinese Agricultural Standard promulgated in NY/T 2267–2012, 2016 "Slow-release fertilizers-General Regulation", the terms/definitions and regulations are much more detailed and refers to the most important nutrient release compounds in slow-release fertilizer, as N, P, and K, respectively: percentage; nutrient release ratio (initial and cumulative using GB/T 22923-2008 Determination of nitrogen, phosphorus and potassium for fertilizers by auto analyzer); nutrients release period/point (GB/T 22924-2008 Determination of biuret content for compound fertilizers) complex fertilizers; etc. Also, an important standard is HG/T 2843-1997 named "Chemical fertilizer Products-standard volumetric, standard, reagent and indicator solutions for chemical analysis". The regulations are made only for N, P, and K fertilizers; the raw materials (must meet the safety requirement, including decomposed chemicals after application); the fertilizer content (N > 30% for urea-based, P > 12 % and K >60 % for compound or complex fertilizers); and release ratio (first in 24 hours <15 %, cumulative release in 28 days <60%, and marked total release time for N). Along with this, China has also promulgated Agricultural Standard for evaluation regulations, NY/T 2274–2012 "Slow-Release Fertilizers-Regulations of efficiency experiment and assessment". This regulation has provided detailed requirements and conditions for evaluating the SRFs, like: General chapter in which is described fertilizing amount, method, crop conditions and its growth period (at least 3 months); Experimental design chapter in which all the results are compared with: a) no fertilizer field, b) regular fertilizing, c) equal nutrients as regular fertilizing, and d) 20% less nutrient content than regular fertilizer. Land size parameter is classified as: a) small trial: 20–30 m^2 for high-density crops (wheat and barley, etc.), and 40–50 m^2 for low-density crops (corn, cotton and tobacco, etc.); b) land trial > 3000 m^2 for economic plans and > 10,000 m^2 for agriculture corps. (*Duan, Q., Jiang, S., Chen, F., et all., 2023).*

The synergy between IBC and EBC standards, in this years, it is noted, because were made efforts to unify the holistic overview, and to combine the researchers efforts to set the proper testing and sapling methodology in order to achieve an biochar's classification into five types, based on their soil potential benefits, as: carbon storage; fertilizer value; liming potential; particle-size classes; use in potting mixes and soilless agriculture.

Also the necessity to add the information's regarding the: feedstock source-provenance, production methods-pyrolysis equipment/installation type; quality control based on commune view of testing and presenting the data (IBI, EBC, BQM, or national laws and regulations), was identified in practical research papers published, but also on: biochar technological viability, possibilities for expansion, expenses, long-term carbon storage, verification and monitoring, and the advantages of its application to different carbon reservoirs (*Fawzy, S., Osman, A.I., Mehta, N., et al., 2022*), economic and environmental impact..

Also, the biochar standards treaties subjects such as: biochar quality, limits for organic contaminants; heavy metals in the environment; specifications regarding feedstock manipulation and storage conditions; transit distance, installation energy efficiency, heat recovery system and manufacturing technique. But, in presented international standards/guidelines, are not specify the soil biochar application rules and rates – direction in which are made efforts substantial efforts to make a same models and methodologies.

For example, a specific case study was conducted, on saline soils having high salinity (more than 4 dS/m), respectively high electrical conductivity (EC). This soils typically leads to osmotic plant and microorganisms stress (*Kotula, L., Caparros P.G, Zörb, C., Colmer, et all., 2020).*

The experts, advise to choose biochar with highest nutrient content and a low liming rate (CaCO3-eq < 1%) to minimize the introduction of extra salts while enhancing the primary productivity of the soil. In the case of saline-sodic soil or sodic soil with an exchangeable sodium percentage (ESP) exceeding 15 or a sodium adsorption ratio (SAR) surpassing 13, the presence of high levels of sodium ions and low levels of salt can lead to significant clay dispersion, degradation of aggregate structure, and the reduction of microporosity

MATERIALS AND METHODS

In many research papers wrote on the subject of animal manure biochar showed a higher potential as nutrient source rather than a C sequestration strategy, then the others vegetal biochar fodders (*Conz R.F., Thalita F., Abbruzzini, C.A.A., et al., 2017*).

In order to structure, analyze and deepen the knowledge wort until now, and to structure the future research, conducted by the most prestigious actors in pyrolysis equipment's producers and researchers, temperature and feedstock type are the key parameters that led the biochar properties of biochar, is necessary and almost mandatory to fallow the standards and guidelines drawn in this moment. In this way will obtain international relevant results for better tailored materials that correspond to the expected results while considering its interactions with environmental conditions and soil specification.

For this reason, will be made a case study of two scientific reports published on biochar properties obtained from pyrolysis treatment using several vegetal and animal dejections feedstocks. The experimental research data were conducted differently and lead to others values. Fist case was made in accordance with the International Biochar Initiative Guideline and in second case using their methodology (that is not entirely described in the paper).

From this reports it will be extract some data regarding the poultry litter feedstock that in the bought cases was mixt with sawdust (the mixture ratio is do not mentioned), because in our research project this category of dejections will be capitalized in agriculture as a natural fertilizer.

Case I - Experiment research conducted according the IBI Guidelines

The experiments were conducted, on several types of fodder such as: sugarcane straws, rice husk, poultry litter and sawdust. The poultry is obtained from a sustainable farm, in which the chickens/hens were fed daily with grass. The manure sits on the ground of the facility and it is mixed with sawdust weekly. This mixture is an important factor for biochar production, because poultry litter is mixt with sawdust, so after pyrolysis process will be trace of hemicellulose, lignin and cellulose. In table 1, were centralized the experimental data obtained. (*Conz, R.F., Abbruzzini, T.F., Andrade, C. A., et al., 2017*).

Pre-treatment included several steps: drying at 45 [˚C] during 24 h; grounding at less than 1 [mm] particle size (where used mortar and pestle and sieved to achieve particle size of 150 until 850 *10 $^{-6}$m.); were taken samples send to do a characterization analysis; prior to pyrolysis, the material has been dried at 105 [˚C] until it reaches proximately 13 % moisture (w/w) to improve the reactor efficiency.

The feedstock was pyrolyzed in a 60 L static reactor in N_2 saturated atmosphere with a heating rate of 10 [˚C·min^{-1}], the reactor was heated by six electrical resistances to the temperatures of 350 [˚C], 450 [˚C], 550 [˚C] and 650 [˚C]. The biochar's were removed from the reactor after 12 [h] from reaction time was completed, in this way it can avoid spontaneous combustion.

The mass of all materials contained in the chamber reaction was determined in order to obtain biochar yield. Feedstocks were analyzed accordingly to the biochar methodologies concerning the determinations of: pH, electrical conductivity (EC); cation exchange capacity (CEC); proximate and elemental analysis, presented in Table 1. Additionally, feedstock samples were evaluated in relation to their devolatilization characteristics, through thermogravimetry analysis. Table 2.

Case II- using their experimental and data extraction methodology

This study was conducted to examine how feedstock and pyrolysis temperature affect the final composition of the biochar with respect to the most commonly used analytical protocols to evaluate biochar agronomic value and stability properties using a large set of samples.

Pre-treatment processing: anaerobically digested dairy manure; compressing to extract the liquid fraction via a screw press and mixed in a 1:1 ratio (w/w) with chipped wood waste just prior to pyrolysis to produce composted dairy manure with wood waste biochar: feedstocks was dried at 60 ^{0}C to ca. 10% moisture (w/w) prior to pyrolysis.

Biochar's were produced using the Daisy Reactor, Best Energies Inc.., pyrolyzing the feedstocks in 50 ^{0}C increments from 300 to 600 ^{0}C (Cashton, WI, USA). Approximately 3 kg of feedstock were manually placed into a main chamber, which was purged at N_2 source, while the mixer was running to uniformly heated chamber for 80–90 min. This period includes both raising the temperature from ambient to target at less than 10 ^{0}C per minute, and holding at the target temperature for 15–20 min. The material was released after the equipment was cooled.

Sample preparation methodology. 1. Air-dry biochar's were mortar and pestle ground, sieved prior to analyses to obtain particle size range of 149–850*10^{3}m. Proximate analysis methods were conducted using ASTM D1762-84 Chemical Analysis of Wood Charcoal, this guide was adjusted to fit with biochar reactivity. A low temperature (LT) method was developed to volatiles determination be more relevant to biochar's. All proximate analyses were performed in duplicate. Mode details can be read in (*Enders, A., Hanley, K., Whitman, T., at al., 2012*). The data collected from the graphs were presented in Tabel 1.

In this case were utilized tests developed for the power industry and for soils, to collect data from biochar characterization. One of them it was so-called ''proximate analysis'', conducted according to ASTM D1762-84 to measure the moisture, volatiles, and ash content, with regard to its use as a fuel. The volatile solution content, *(Zimmerman, 2010),* to determine the stability of the material and effects on N availability.

For biochar's the ash ratio is related to metals volatilization at the high temperatures used by ASTM method.

Table 1

Poultry litter biochar properties according the IBI standards & others

Parameter value & M.U	**Pyrolysis temperature (^{0}C)**				**Feed -stock**	**Pyrolysis temperature (^{0}C)**						
	350	**450**	**550**	**650**		300	350	400	450	500	550	600
Yield [%]	59,6	47,1	42,0	40,2	-	78	75	70	68	70	69	70
EC [mS/m]	4,4	3,9	3,5	4,0	11,4	-	-	-	-	-	-	-
pH	8,2	9,8	9,8	9,9	7,3	values 9.5 until 9.9						
CEC [mmol$_c$ /kg]	320	203	106	105	597	-	-	-	-	-	-	-
Volatile matter [%]	60,8	46,9	45,7	42,1	69,7	88	-	92	-	95	-	100
Fixed Carbon [%]	0,0	1	2,8	7,5	0	10	-	8	-	7	-	5
Ash [%]	38,2	51,0	50,3	48,8	29,7	50	-	55	-	56	-	58
P [g/kg]	3,72	2,13	3,51	4,28	-	1	0.8	0.6	0.7	1.3	0.8	1
K [g/kg]	3,13	1,78	2,48	3,05	-	1	0.8	0.6	0.7	1.2	0.8	0.9
Mg [g/kg]	1,16	0,74	1,03	1,28	-	1.5	1.4	1.3	1.2	1.5	1.3	1.4
S [g/kg]	0,76	0,39	0,6	0,65	-	1	0.8	0.6	0.7	1	0.6	0.8
Fe [mg/kg]	0,44	0,34	0,45	0,56	-	-	-	-	-	-	-	-
Mn [mg/kg]	0,05	0,04	0,05	0,06	-	-	-	-	-	-	-	-
Zn [mg/kg]	0,09	0,05	0,08	0,08	-	-	-	-	-	-	-	-
N [%]	-	-	-	-	-	82	65	40	38	39	38	30
C [%]	38.1	29.8	35.3	32.6	30.4	98	86	89	90	78	75	80
O [%]	55.9	68.5	61.5	65.1	62	-	-	-	-	-	-	-
H [%]	3.4	1.7	1.4	0.9	4.5	-	-	-	-	-	-	-
Certified Standard Parameters	Case I (*Conz, R.F., Abbruzzini, T.F., Andrade, C. A., et al., 2017*)					Case II *(Enders, A., Hanley, K., Whitman, T., at al., 2012)*						

Form above results presented numerically in the Table 1, it can be observed that:

- the animal manure derived biochar is shown to accumulate important elements, such as phosphorus, calcium and magnesium. Thus, animal manure derived biochar has higher potential to be used as a nutrient source in agricultural systems, conclusion that was drawn in both cases, (*Azargohar, R., Nanda, S., Kozinski, J.A., et al. 2014*), but with different values,

- macronutrients concentration in biochar increases during the pyrolysis process while volatile matter and water is released from biochar structure. These latter compounds are represented by organic acids, and as pyrolysis temperature increases, the release of such molecules and the accumulation of basic elements such as Ca and Mg are the drivers of high pH in biochar's. These properties support the use of biochar as soil amendment as liming agent and nutrient source, in bought cases, *(Ippolito, J.A., Spokas, K.A., Novak, J.M., at al., 2015).*

- the biochar's derived from manures, accumulates C at different rates by increasing temperature, in bought cases, but this category of feedstock has the property, to lower C quantities in relation to nutrients, *(Ippolito, J.A., Spokas, K.A., Novak, J.M., at.al. 2015).*

- animal manure biochar, presents high ash materials, such as have high inorganic C content bound to carbo-nates, which can decrease the C by 24%, aspect present also in other papers *(Cimo, G., Kucerik, J., Berns, A.E, at al.,2014).*

- the CEC reduction, represents the release of carbonyl and carboxyl organic, fact that represents a decree in intensity. (*Conz R.F., Thalita F., Abbruzzini, C.A.A., et al., 2017*).

- also, was made a FTIR spectroscopy, analyse used to show biochar broadening and flattening with temperature evolution, (*Conz R.F., Thalita F., Abbruzzini, C.A.A., et al., 2017*), fact that indicates loss of: labile aliphatic and toxic compounds (*Kloss, S., Zehetner, F., Dellantonio, A., et al., 2012*); recalcitrant compounds maintenance, such as aromatic chains, specifically, loss of aliphatic C-H bond (*Wu, W., Yang, M., Feng, Q., at all., 2012*); the absence of functional groups represent the pyrolysis of cellulose, hemicellulose and lignin sawdust biochar's, around 1030 cm−1 (*Cantrell, K.B., Hunt, P.G., Uchimiya, M., at all., 2012, Nanda, S., Azargohar, R., Kozinski, J.A. at all., 2014);* the cumulative mass loss was the lowest in poultry manure within the temperature range analyzed (from 25˚C to 600˚C), which was also found by (*Ghani, W.A.K., Ayaz Mohd, A., Silva, G., et al., 2013*).

RESULTS

Many researchers have done experiments on biochar production and administration, but the data where unreliable, because were made in accordance with their needs and feedstock type available: hens or chickens feed with grass or cereals; the poultry litter is mixed with many types of vegetal/ wood subproducts in different concentrations; and the pyrolysis is not always done in the same conditions (installation type, pyrolysis regime, etc.).

So, most of them proposed and sustained the need to unify and agree to draw some guidelines and regulations to obtain from now one reliable results and technologies, in order to elaborate biochar administration mythology properly designed for a sustainable agriculture, poor field, polluted areas or degraded lends, in order to make a safety environment and to reduce air-water-soil pollution.

Based on the above presented results, were drawn important observations, that now have a scientific base applying the IBI guidelines, observations that also are present in scientific paper works published until the publications of guidelines.

In this part will be drawn important concussion recognizing the value of poultry litter biochar and its properties which recommends it to be used in agriculture:

1. Hence poultry litter showed the highest EC values since animal derived feedstock, that usually contain higher nutrient concentration (*Singh, B., Singh, B.P., Cowie, A.L. 2010)*. Particularly for poultry litter biochar's, the decrease in EC and is related with ash increase concentration, and when compared with its feedstock showed much higher values, corroborated with literature. (*Meng, J., Lili Wang L., Liu, X., et al., 2013);*
2. Poultry litter biochar exhibited the highest values of basic salts found in its feedstock, corroborating with the higher concentration. (*Lehmann, J., Rillig M.C., Thies, J., et al.,2011);*

3. The loss of acidic functional groups is due to pyrolysis temperature action was actually observed for poultry litter and sawdust. The CEC was expected to be smaller, in comparison to the respective original biomasses. (*Zhao, L., Cao, X., Masek, O., et all., 2013; Wang, Y., Hu, Y., Zhao, X., at all. 2013);*
4. Poultry litter biochar showed the greatest values for macronutrients especially due to high content of Ca, which explains the higher pH determined for this material *(Kloss, S., Zehetner, F., Dellantonio, A.,et all., 2012)*. The macronutrient content, per total, obtained from animal derived biochar's was higher compared to crop residues and wood derived materials;

5. Contents of P and K found, in case II, were lower than other results found in the literature and also in the IBI guides (case I), due to differences in methodology to elements determine concentration and heterogeneity of poultry litter feedstock. (*Cantrell, K.B., Hunt, P.G., Uchimiya, M., et all., 2012; Song, W. and Guo, M., 2012*);

6. The poultry litter biochar presents significant amounts of mineral analysed elements, compared to other feedstock materials studied, even though the concentrations dropped with temperature increase, justifying its potential use as fertilizer. (*Meng, J., Lili Wang L., Liu, X., et all., 2013*);

7. Poultry litter consist in highest zinc (Zn) concentration, reaching 0.09 ppm, which reflectes the common addition of Zn as a supplement in poultry diet (*Park, S., Birkhold, S., Kubena, L., et all., 2004*). Fact that represents the potential use of biochar's as soil amendment;

8. Rate of ash content is high at poultry litter biochar, which corroborates with literature. Animal derived biochar composition can reach approximately 50% of ash content, and sometimes between 45% and 60% of volatile matter, results similar of those reported by (*Song, W. and Guo, M. 2012), and (Meng, J., Lili Wang L., Liu, X., et all. 2013*);

9. For instance, poultry litter (30% to 40%) showed slightly decreasing content with increasing temperature. High ash materials, have high inorganic C content bound to carbo nates, which can decrease the C by 24% (*Enders, A., Hanley, K., Whitman, T., et all., 2012; Cimo, G., Kucerik, J., Berns, A.E, at all., 2014*).

10. The cumulative mass loss was the lowest in poultry manure and rice hull within the temperature range analysed (from 25˚C to 900˚C), which was also found by (*Azargohar, R., Nanda, S., Kozinski, J.A., et all., 2014; Ghani, W.A.K., Ayaz Mohd, A., Silva, G., et al., 2013*).

11. The higher proportion of volatile matter determined in the poultry litter biochar, indicates higher amount of easily degradable source of C, enabling its use by the microorganisms, which in turn cause soil respiration to spike when comparing to control treatment.

12. It is essential to note that agricultural properties, that support the use of biochar as nutrient source, were improved in manure derived biochar's, while C stability was lower. (*Conz, R.F., Abbruzzini, T.F., Andrade, C. A., et all., 2017).*

CONCLUSIONS

These confirmations are important for scientific research community, in order to recognise the value of the pass experiences and their results, which represent the bases of these regulations.

Aster this case study was identify a need to add and to standardize the thermogravimetric analyses, because could add value and results replicability, also helps to scaleup biochar thermal devolatilization. (*Enders, A., Hanley, K., Whitman, T., et all., 2012*).

Currently the most accessible approach to evaluate recalcitrance is the elemental contents analyse, pH, NPH influence that influence the plant responses.

Higher soil aggregation was also observed for fine-textured soil where wood and animal derived biochar was added (*Wang, D., Fonte, S.J., Parikh, S.J., et all., 2017),* improving soil physical structure, aeration and moisture ratio, consequently an improved environment for root development.

These mechanisms are often related to increased agricultural production; however, results vary due to biochar properties and its interaction with different environmental conditions (*Lorenz, K. and Lal, R., 2014*).

A new trend is now, determination of biochar toxic effects (PAH's, PCDD/Fs, PCB's, As, d, Cr, Cu, Pb, Hg, Ni, Zn), that according to some scientists alters soil physical attributes, toxicity, humidity, if is applied outside the agronomic application rate.

Sometimes, these hazards can be avoided if isn't taken in to consideration all environmental factors, like: clime, soil specifications, vegetal fauna/ crop specifications, rain drops rates, microorganism population and fauna, and in this way the biochar is efficiency used. (*Enders, A., Hanley, K., Whitman, et all., 2017).*

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CREATING A DATABASE FOR ARTIFICIAL INTELLIGENCE TRAINING
/
CREAREA UNEI BAZE DE DATE CU SCOPUL ANTRENARII INTELIGENCEI ARTIFICIALE

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Keywords: *dataset, data gathering, artificial intelligence, machine learning*

ABSTRACT
The development of well-structured databases is the first step in the usage of artificial intelligence (AI) systems. This paper presents the methodology and design used in creating a database intended for AI training. Importance is placed on data collection strategies, preprocessing techniques, and quality assurance measures to ensure the accuracy, diversity, and scalability of the dataset. The study focuses on ethical and technical challenges associated with dataset construction, including bias mitigation, and long-term maintainability. The resulting database is evaluated in terms of its applicability to machine learning models and its potential to support future research in AI training.

REZUMAT
Dezvoltarea unor baze de date bine structurate este primul pas în utilizarea sistemelor de inteligență artificială (IA). Această lucrare prezintă metodologia și designul utilizate în crearea unei baze de date destinate instruirii în domeniul IA. Se pune accent pe strategiile de colectare a datelor, tehnicile de preprocesare și măsurile de asigurare a calității pentru a asigura acuratețea, diversitatea și scalabilitatea setului de date. Studiul se concentrează pe provocările etice și tehnice asociate cu construirea setului de date, inclusiv atenuarea erorilor de prejudecată și mentenabilitatea pe termen lung. Baza de date rezultată este evaluată în ceea ce privește aplicabilitatea sa la modelele de învățare automată și potențialul său de a sprijini cercetările viitoare în domeniul instruirii în domeniul IA.

INTRODUCTION

According to (*Gong et al., 2023*), with the rise of big data, the quality of datasets has become a crucial factor affecting the performance of machine learning models. High-quality datasets are essential for the realization of data value. As per (*Hernández López et al., 2022*), the application of machine learning (ML) algorithms to address problems related to model-driven engineering (MDE) is currently hindered by the lack of curated datasets of software models. Training data preprocessing has a great impact on the model's predictive performance, is highly dependent on the modeler's experience, and is not typically reported in engineering-related literature.

The objective of this study was to assess the effects of data preprocessing, hyperparameter selection, and time series size on the model's evaluation metrics, based on a study by (*Aranha et al., 2023*). Supervised learning techniques are ML learning techniques or algorithms that bind previous and current dataset with the help of labeled data to predict future events (L. J. Muhammad et al., 2021) and prevailing data practices tend to abstract away the human labor, subjective judgments and biases, and contingent contexts involved in dataset production (*Paullada et al., 2021*).

It is an undeniable fact that currently information is a pretty significant presence for all companies or organizations (*Yavanoglu et al., 2017*), and that is mainly the reason we chose to create our own. As per (*Eastman et al., 2023*), any machine learning model is only as good as the data it is trained on. (*Mahani et al., 2025*) points out that acquiring a substantial number of data points for training accurate machine learning (ML) models is a big challenge in scientific fields where data collection is resource-intensive. According to (*Gauen et al., 2017*), among all factors that contribute to this development, datasets with labels play crucial roles, which is the reason we chose to focus on creating our own database.

MATERIALS AND METHODS

The datased is composed of around 900 photos (in .PNG format at 1920x1080 resolution), with each photo showing approximately 50-60 different tomoatoes of varied cultivars. The photos included were exclusively gathered locally in the greenhouses of INMA Bucuresti and INCDIBH Ștefănești, taken on varied light conditions: at morning (7:00-11:00) over the course of 2 months, July and August.

The gathering of the photographs also varied in more aspects, such as camera distance from the plant (between 30cm to 1m), or the angle of the camera (between -10° and 40°).

Fig. 1 - Different views of the platform and support used for gathering data

As for hardware, the data was gathered using both a ZED i2 camera and a Logitech HD Pro C920, mounted on a support with adjustable distance and height.

The system was moved trough the greenhouses along a path of railways, using a mobile platform. Both the adjustable system and the mobile platform were designed, created and assembled at INMA Bucharest.

Fig. 2 - Railways lain between lanes of tomato plants inside greenhouse

As stated by (*Michelini et al., 2021*), a relevant aspect when compiling a large dataset to be used for ML purposes consists of gathering a balanced distribution of data. We have chosen to categorize the individual tomatoes of each photograph using three classes: c_ripe, c_half-ripe and c_green.

For labeling we have the LabelStudio software, exporting YOLO.TXT files. Using the software for manually labeling each of the approximately 28 000 instances took around 2 months of work, split among 5 people. This process helps guarantee the high precision for differentiating ripe tomatoes from green or half-ripe tomatoes.

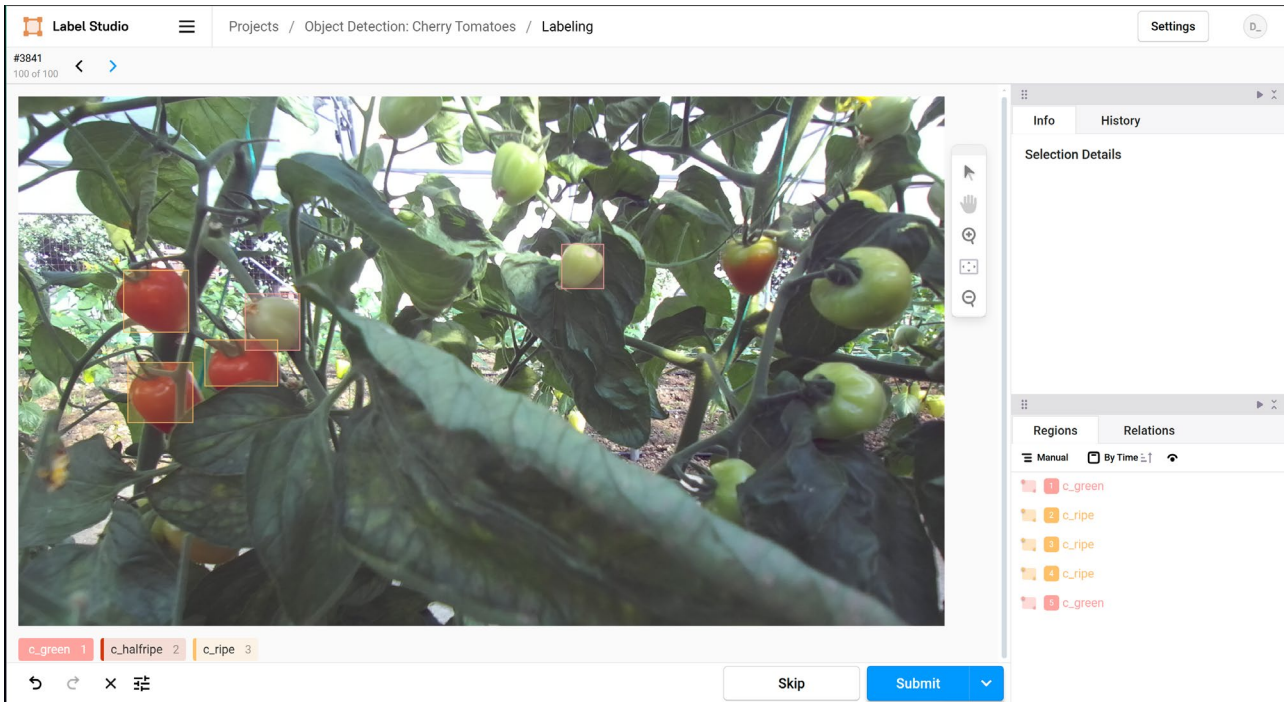

Fig. 3 - Process of using the LabelStudio software for processing gathered data

Part of the hardware used for gathering the photographs was Stereolabs ZED 2i stereo depth camera (Stereolabs Inc., San Francisco, USA). The device consists of two 4-megapixel CMOS sensors mounted in a fixed stereo configuration with a 120 mm baseline, enclosed in an IP66-rated aluminum housing suitable for indoor and outdoor use. It provided a field of view of approximately [-10° / 40°]* horizontally.

The ZED 2i records synchronized stereo image pairs at multiple resolutions (up to 2×2208 × 1242 pixels at 15 fps), from which depth maps are computed using Stereolabs' neural stereo engine. The effective depth sensing range is approximately 0.3–20 m with the 2.1 mm lens (up to 35 m with the 4 mm lens).

In addition to stereoscopic imaging, the camera integrates a 9-DoF inertial measurement unit (IMU), magnetometer, and barometer, enabling visual-inertial odometry and improved spatial tracking. Data were transmitted via a USB-C 3.0 interface to a host computer for processing using the ZED SDK.

Simultaneously, a Logitech HD Pro Webcam C920 (Logitech International S.A., Lausanne, Switzerland) was used to capture high-definition data. The device employs a dual-microphone system and a Carl Zeiss® glass lens with autofocus, capable of recording at resolutions up to 1920 × 1080 pixels (Full HD) at 30 frames per second. Still images can be captured at resolutions up to 15 megapixels (software-enhanced).

Fig. 4 - Stereolabs ZED 2i stereo depth camera

The webcam connects via a USB 2.0 interface and is compatible with most major operating systems without additional drivers. Automatic light correction and autofocus features allow it to adapt to different illumination conditions, making it suitable for stable, continuous data collection in varied environments.

Fig. 5 - Logitech HD Pro Webcam C920 camera

RESULTS

The collection was organised into a folder unit (photographs and labels), which allowed us to make use of the newly created dataset for directly training and validating AI models. The dataset is built on the standard YOLO format, organised in distinct folders (train, valid and test), which, in turn, contain photographs and label files. Each photograph correlates to an associated .TXT file containing bounding box's coordinates and each individual tomato's class. The connection between photographs and labels is guaranteed by the configuration file .YAML, contained within the dataset.

The roughly 28 000 instances were split between the 3 classes as follows: approximately 19 000 for the c_green class, approximately 6000 for the c_ripe, and approximately 3000 for the c_half_ripe class. Noting the high distribution of instances for the unripe class, this was necessary for having an accurate differentiation between tomatoes (of green color) and the rest of the plant (also green).

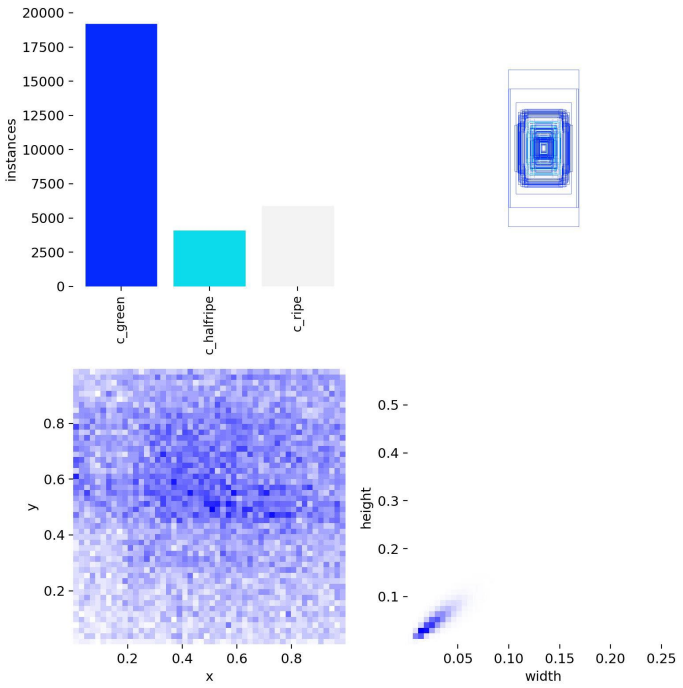

Fig. 6 - Visual representation of class distribution

CONCLUSIONS

In this work, we presented the collection of a dedicated image dataset designed to support the development and training of machine learning models for tomato classification. The dataset was curated under varied acquisition conditions and structured into clearly defined classes, which guaranteed the diversity and reliability of the samples. By providing a sufficiently large and well-labeled set of instances, this dataset offers a valuable foundation for advancing automated recognition tasks in agricultural research and practice. Future work will focus on applying and evaluating machine learning techniques on this dataset to assess performance and explore its potential for further deployment.

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ENHANCING SOIL SAMPLING ACCURACY THROUGH IOT INTEGRATION
/
ÎMBUNĂTĂȚIREA PRECIZIEI EȘANTIONĂRII SOLULUI PRIN INTEGRAREA IOT

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Keywords: *????*

ABSTRACT

This paper aims to explore and summarize how Internet of Things (IoT) technologies can be integrated into soil sampling systems to enhance precision, efficiency, and automation in agricultural practices. By implementing IoT-based solutions, soil sampling can transition from a manual, time-consuming task to a data-driven, automated process capable of providing continuous and accurate information about soil conditions. Through the collection of detailed soil data—such as moisture levels, temperature, nutrient composition, and pH, farmers can gain a deeper understanding of soil health and stability, which are critical factors in achieving optimal crop growth. The introduction of IoT-enabled soil sampling systems, combined with cloud computing for data storage and processing, offers the potential to fully automate sampling operations using remotely controlled or self-navigating machinery. Such systems can precisely identify sampling points, record their geographic locations using GPS technology, and store the results in real time for immediate or later analysis. This automation not only eliminates the need for manual labor and field driving but also ensures consistency and repeatability in the sampling process.Furthermore, integrating IoT, cloud computing, and artificial intelligence could enable predictive analytics, allowing for early detection of soil nutrient deficiencies or environmental stress factors. As a result, farmers could implement targeted interventions, such as optimized fertilization or irrigation strategies, leading to healthier crops and increased yields. Overall, the adoption of IoT in soil sampling represents a crucial step toward the digital transformation of agriculture, improving productivity, reducing costs, and supporting more sustainable and environmentally responsible farming practices.

REZUMAT

Această lucrare își propune să exploreze și să prezinte modul în care tehnologiile Internet of Things (IoT) pot fi integrate în sistemele de eșantionare a solului pentru a spori precizia, eficiența și automatizarea practicilor agricole. Prin implementarea soluțiilor bazate pe IoT, eșantionarea solului poate trece de la o sarcină manuală, consumatoare de timp, la un proces automatizat, bazat pe date, capabil să ofere informații continue și precise despre condițiile solului. Prin colectarea de date detaliate despre sol cum ar fi nivelurile de umiditate, temperatura, compoziția nutrienților și pH-ul, fermierii pot obține o înțelegere mai profundă a sănătății și stabilității solului, care sunt factori critici în obținerea unei creșteri optime a culturilor. Introducerea sistemelor de eșantionare a solului bazate pe IoT, combinată cu cloud computing pentru stocarea și procesarea datelor, oferă potențialul de a automatiza complet operațiunile de eșantionare utilizând utilaje controlate de la distanță sau cu auto navigare. Astfel de sisteme pot identifica cu precizie punctele de prelevare, pot înregistra locațiile lor geografice folosind tehnologia GPS și pot stoca rezultatele în timp real pentru analiză imediată sau ulterioară. Această automatizare nu numai că elimină necesitatea muncii manuale și a conducerii pe teren, dar asigură și consecvența și repetabilitatea procesului de eșantionare. În plus, integrarea IoT, cloud computing-ului și inteligenței artificiale ar putea permite analiza predictivă, permițând detectarea timpurie a deficiențelor de nutrienți ai solului sau a factorilor de stres din mediu. Prin urmare, fermierii ar putea implementa intervenții specifice, cum ar fi strategii optimizate de fertilizare sau irigare, ceea ce ar duce la culturi mai sănătoase și la randamente sporite. Per total, adoptarea IoT în prelevarea de probe de sol reprezintă un pas crucial către transformarea digitală a agriculturii, îmbunătățind productivitatea, reducând costurile și susținând practici agricole mai sustenabile și mai responsabile din punct de vedere ecologic.

INTRODUCTION

Contemporary agriculture remains predominantly dependent on human labor and manually operated machinery, despite significant technological advancements and concerted efforts to promote automation. Although automated systems and smart farming technologies are increasingly available, their widespread adoption is constrained in numerous regions by several critical barriers. These include prohibitive implementation costs, a deficit of technical expertise, and insufficient infrastructural support. Consequently, traditional methodologies continue to prevail, underscoring a critical need for more accessible and pragmatically integrated automated solutions to enhance agricultural productivity and operational efficiency. (*Huuskonen and Oksanen, 2018*).

Fig. 1 - Hand held soil sampling probe
(https://www.winfieldunited.com/news-and-insights/spring-soil-sampling-is-no-longer-optional)

Soil is a mixture of organic matter, minerals, gases, liquids, micro and macroorganisms that together support life. Soil sampling is a fundamental practice in agriculture, environmental monitoring, and land management. Accurate soil sampling allows researchers and farmers to evaluate soil fertility, detect contamination, and make informed decisions about crop management, fertilization, and sustainability strategies. However, traditional soil sampling methods are often manual, labor-intensive, time-consuming, and prone to human error, which can compromise data reliability and reproducibility. Soil testing enables the planning of cultivation and soil management actions as well as providing the basis for a sustainable crop nutrition programme that is accurate, timely and increasingly importantly environmentally responsible (*Abate Gezahagn Goshu, 2024*).

Around the globe agriculture provides for every human the most basic need for food and fiber. The common effort of researchers to introduce new farming techniques in the past century has helped agriculture satisfy the ever-growing population demands for food and agricultural products. However, as the global population continues to grow and income levels rise, the demand for food is expected to increase significantly, placing even greater pressure on already limited natural resources. This situation highlights the urgent need for more sustainable and efficient agricultural practices. With increasing awareness of the environmental consequences of conventional farming such as soil degradation, water scarcity, and greenhouse gas emissions it has become essential to adopt innovative methods that can meet future food requirements while minimizing or even reducing agriculture's ecological footprint. Emerging technologies like geospatial mapping, the Internet of Things (IoT), Big Data analytics, and artificial intelligence (AI) offer powerful tools to address these challenges. By integrating these technologies, farmers and researchers can make more informed and precise management decisions, optimize resource use, and ultimately enhance crop productivity in a sustainable manner (*Sishodia et al., 2020*).

The Internet of Things (IoT) refers to a network of physical objects embedded with sensors, software, processing capabilities, and other technologies that enable them to connect and exchange data with other devices and systems over the internet or through various communication networks. By leveraging IoT technology, agricultural machinery can be remotely operated and monitored, significantly reducing or

even eliminating the need for manual field labor. This approach not only minimizes human involvement in repetitive or physically demanding tasks but also enhances the precision, consistency, and overall efficiency of farming operations. As a result, IoT-driven automation allows for better resource management, improved productivity, and more sustainable agricultural practices (*Rajasekaran et al., 2024*).

Cloud computing is a technology that enables the sharing and management of computing resources at a relatively low cost. Service providers offer these cloud-based resources in an affordable and scalable manner, making data storage and processing more accessible for various applications. In agriculture, cloud computing plays a vital role when combined with Internet of Things (IoT) technologies, facilitating the collection, analysis, and storage of large volumes of agricultural data. The integration of artificial intelligence (AI) and cloud computing provides a powerful support system for IoT-based agricultural solutions. This combination allows data gathered from intelligent wireless sensors—such as those mounted on unmanned aerial vehicles (UAVs), satellites, and agricultural machinery—to be processed and analyzed efficiently. Additionally, robotic systems like unmanned ground vehicles (UGVs) equipped with precise positioning tools, including real-time kinematic (RTK) GPS and LiDAR sensors, contribute to high-resolution field monitoring and management. Underpinning these systems is the Wireless Sensor Network (WSN), a network composed of spatially distributed sensor nodes that communicate wirelessly to gather and transmit environmental and operational data for centralized processing in the cloud (*Alahmad et al., 2023*).

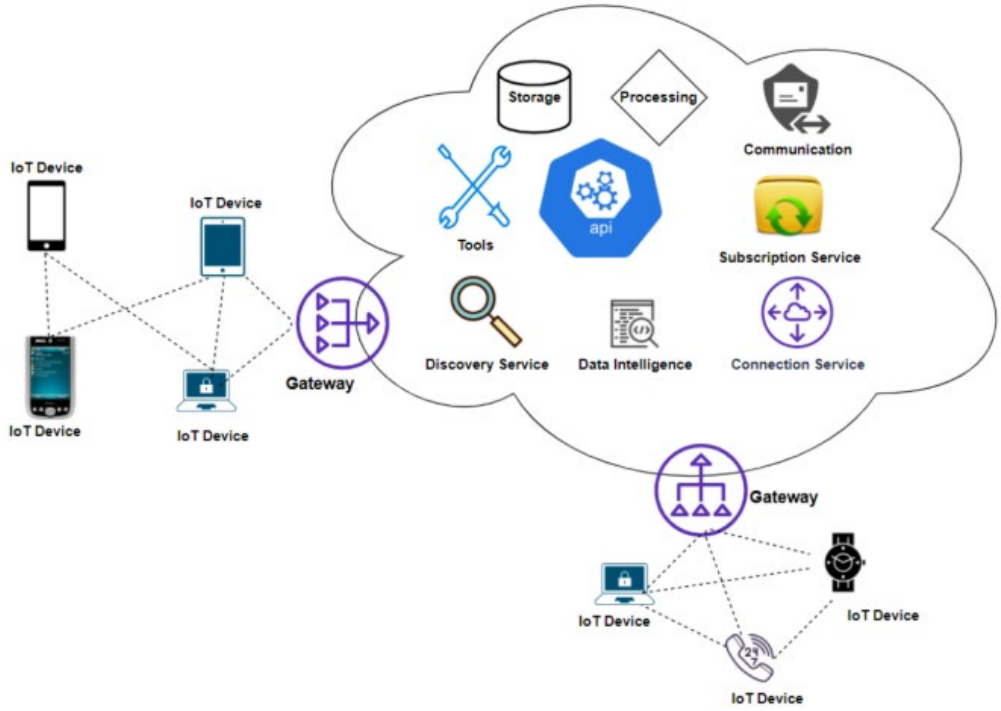

Fig. 2 - IoT System Based on Cloud
(Alam T., 2021)

MATERIALS AND METHODS

2.1 Robot navigation method.

The integration of Global Positioning System (GPS) technology with Internet of Things (IoT)-based sensors establishes a framework for automating and enhancing the precision of soil sampling. A robotic platform equipped with a high-accuracy GPS module can autonomously navigate a field and geotag the precise coordinates of each sampling point. This positional data is augmented by a depth sensor or ultrasonic device that monitors the penetration of the sampling probe, ensuring consistent and reproducible sampling depth across the field. Furthermore, a suite of onboard environmental sensors—capable of measuring parameters such as soil moisture, temperature, and electrical conductivity—can collect supplementary in-situ data. This real-time sensor data provides critical context for interpreting subsequent laboratory analyses and contributes to the generation of high-resolution soil property maps. All sensory data is aggregated and communicated via an IoT network, utilizing wireless protocols (e.g., LoRaWAN, 4G/5G) for real-time transmission to a central base station or cloud platform. This centralized system processes the incoming datastream, visualizes the georeferenced sampling points on a digital field map, and creates a

structured database that links each physical sample with its corresponding geographic position and ambient field conditions.

Consequently, this integrated technological synergy enables the accurate identification of spatial nutrient distribution patterns while significantly mitigating the potential for human error intrinsic to manual sampling methodologies. In summary, the confluence of GPS, IoT communication, and automated sensing facilitates a highly efficient, repeatable, and data-driven paradigm for soil sampling and analysis.

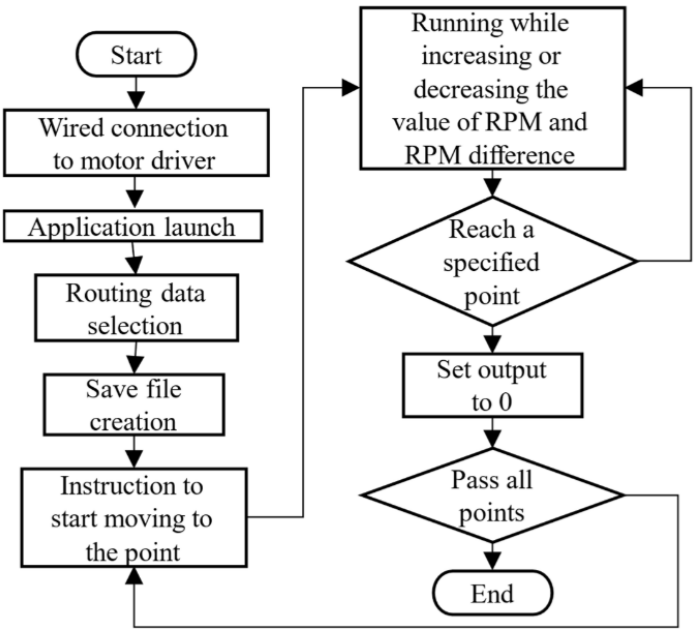

Fig. 3 - Automatic driving flowchart of a robot that uses GNSS technology to gather soil samples
(Yang et al., 2025)

In addition, ultrasonic and infrared sensors are employed to detect obstacles such as rocks, plants, uneven ground, or farming equipment in the robot's path, thereby preventing collisions and potential damage during movement. These sensors constantly emit waves or light signals and measure the time it takes for them to bounce back, enabling the robot to determine the distance to nearby objects with high accuracy. Combined with proximity detection algorithms, they allow the robot to slow down, stop, or reroute in real time when an obstacle is detected. A gyroscope and accelerometer, often integrated as part of an inertial measurement unit (IMU), are used to maintain stability, orientation, and direction, especially when operating on irregular or sloped terrain. This ensures that the sampling mechanism remains steady and that the robot maintains balance throughout its operation.

Additionally, wheel encoders are utilized to measure the distance traveled and the rotational speed of the robot's wheels, which helps correct positioning errors that may occur when GPS signals are weak or temporarily unavailable. By continuously comparing encoder readings with data from the IMU and GPS, the system can estimate the robot's precise location and orientation through sensor fusion techniques. All these navigation sensors communicate with an onboard processing unit, which integrates the incoming data, performs real-time analysis, and dynamically adjusts the robot's trajectory to maintain an optimal and safe path. This intelligent coordination of sensing and control not only guarantees autonomous and collision-free navigation but also enhances operational reliability, efficiency, and adaptability in complex and changing agricultural environments (*Chen et al., 2025*).

At the core of the robot's navigation and control system is a Raspberry Pi, which acts as the central processing unit responsible for coordinating all onboard sensors and actuators. It collects data from the GPS, ultrasonic and infrared sensors, inertial measurement unit (IMU), and wheel encoders, processing this information in real time to determine the robot's position and surroundings. The Raspberry Pi executes navigation algorithms, interprets sensor inputs, and issues control signals to the motors or steering mechanisms to ensure accurate and stable movement. Additionally, it handles wireless communication with the cloud or base station via Wi-Fi, LoRa, or 4G modules, allowing continuous monitoring and data logging. Its versatility, low power consumption, and compatibility with open-source platforms make it ideal for IoT-based agricultural systems. In essence, the Raspberry Pi functions as the robot's "brain," integrating sensing,

decision-making, and control functions to enable safe, autonomous, and efficient soil-sampling operations (*Joice et al., 2025*).

2.2 Sampling Method

The robot moves to a predetermined GPS coordinate, where it deploys a mechanical gathering mechanism to extract soil from specific depths. This mechanism usually consists of a vertical drill, auger, or hollow probe that penetrates the ground to collect a core sample. The depth sensor ensures that the gathering device reaches the exact desired depth, maintaining consistency across all sampling points. Once the sample is collected, the system either deposits it into a container or stores it in a labeled compartment, often marked with a QR code or digital ID linked to its GPS location.

Some advanced robots use pneumatic or hydraulic actuators to push and retract the gathering tool smoothly, reducing soil disturbance and ensuring high-quality samples. The soil is then automatically transferred into sealed containers inside the robot's storage unit, preventing contamination. After completing the sampling sequence, the robot navigates to the next point or returns to its base station for unloading. This automated approach significantly improves repeatability, and ensures precise georeferencing of every soil sample collected (*Yang et al., 2025*).

Fig. 4 - Automated soil sampling robot designed by Rogo Ag
(https://rogoag.com/)

2.3 Automated docking

Upon completion of its pre-defined sampling route, the robotic system will automatically navigate to a base station or a designated collection point for sample processing. This return transit is executed by either retracing the collection path or following a pre-optimized route back to the docking station. At the station, the system initiates an automated sequence for data upload and sample transfer. Each soil sample is housed in an individual cartridge encoded with a unique digital identifier (e.g., a QR code), which is linked to its precise GPS coordinates and sampling depth.

This automated identification eliminates the need for manual sample logging, thereby enhancing traceability and reducing potential human error. The cartridges are subsequently prepared for transport, where they can be manually retrieved or automatically conveyed for laboratory analysis of key chemical and physical properties, including pH, macronutrient content (nitrogen, phosphorus, potassium), and organic matter. Concurrently, the robot's onboard computing system (e.g., a Raspberry Pi) transmits the complete field dataset to a centralized cloud platform using standard wireless protocols such as Wi-Fi, 4G, or LoRa. This dataset encompasses all georeferenced sample locations alongside in-situ sensor readings like soil moisture and temperature.

The cloud infrastructure organizes this information, creating a structured database that is later enriched with the corresponding laboratory results. This integrated dataset is then visualized using geographic information system (GIS) software to generate detailed spatial maps illustrating the variability of soil nutrients and other properties across the field. These maps provide an empirical basis for variable-rate application (VRA) of fertilizers and precision irrigation, enabling data-driven agronomic decisions. Finally, the

system concludes its cycle by automatically initiating a recharge cycle at the docking station, ensuring operational readiness for subsequent missions. This closed-loop process—spanning autonomous collection, seamless data integration, and cloud-based analytics—significantly augments the accuracy, efficiency, and scalability of soil management, contributing to more productive and sustainable agricultural systems.

CONCLUSION

The integration of Internet of Things (IoT) technologies into soil sampling represents a significant step toward the automation and modernization of agricultural practices. By combining GPS navigation, environmental sensors, and cloud-based data management, soil-sampling robots can collect highly accurate, georeferenced samples with minimal human intervention. This technological approach not only improves the precision and repeatability of soil data but also saves time, reduces labor costs, and minimizes human error. Once collected, the samples and their associated data can be transmitted to cloud platforms, where they are processed, analyzed, and visualized to generate detailed soil nutrient and condition maps. These insights allow farmers and researchers to make informed decisions regarding fertilizer application, irrigation, and crop rotation, ultimately leading to increased productivity and more sustainable farming practices.

Furthermore, integrating IoT with cloud computing, artificial intelligence, and autonomous navigation lays the groundwork for a fully connected and intelligent agricultural ecosystem. As these technologies continue to advance, the potential for large-scale adoption of automated soil-sampling systems will grow, contributing to the broader vision of precision agriculture - a farming approach that optimizes resource use, enhances crop yields, and supports environmental conservation. In conclusion, IoT-driven soil sampling is not merely a technological improvement but a transformative innovation that bridges automation, data analytics, and sustainability in modern agriculture.

ACKNOWLEDGEMENTS:

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ADVANCES IN PARTICLE CHARACTERIZATION OF BERRY FRUIT POWDERS: A COMPARATIVE ANALYSIS OF CONVENTIONAL AND AI-BASED METHODS

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PROGRESE ÎN CARACTERIZAREA PARTICULELOR PULBERILOR DE FRUCTE DE PĂDURE: O ANALIZĂ COMPARATIVĂ A METODELOR CONVENȚIONALE ȘI BAZATE PE INTELIGENTĂ ARTIFICIALĂ

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ABSTRACT

Morphological characterization of particles in berry fruit powders is fundamental for understanding and optimizing their functional properties, such as flowability, solubility, and stability. A variety of particle sizing methods and instruments are available, each based on different physical principles and suited to the specific properties of plant materials. However, studies in the literature show that applying different techniques to the same sample can yield highly variable results, which complicates the interpretation and comparison of the data. This paper compares different particle sizing methods, including conventional approaches, such as sieve analysis, laser diffraction, optical microscopy, X-ray micro-computed tomography and modern AI-based techniques, particularly image analysis integrated with neural networks. In addition to outlining the operational principles, the review evaluates key factors, including measurement accuracy, reproducibility, sample compatibility, and the level of data processing required. AI-based tools are evaluated for their ability to enhance automation, perform real-time monitoring, and extract advanced morphological features. Challenges associated with method standardization, data comparability, and their implementation in industrial workflows are also discussed. The present analysis aims to support researchers and process engineers in selecting appropriate and scalable methods for accurately determining particle size and shape in applications that involve berry fruit powders.

REZUMAT

Caracterizarea morfologică a particulelor din pulberile de fructe de pădure este fundamentală pentru înțelegerea și optimizarea proprietăților lor funcționale, cum ar fi capacitatea de curgere, solubilitatea și stabilitatea. O varietate de metode și instrumente de măsurare a dimensiunii particulelor sunt disponibile, fiecare bazându-se pe diferite principii fizice și fiind adaptate la proprietățile specifice ale materialelor vegetale. Totuși, studiile din literatura de specialitate arată că aplicarea unor tehnici diferite asupra aceleiași probe poate genera rezultate extrem de variabile, ceea ce complică interpretarea și compararea datelor. Această lucrare compară diferite metode de determinare a dimensiunii particulelor, inclusiv abordările convenționale, precum analiza prin sită, difracția laser, microscopie optică, micro-tomografia computerizată cu raze X, precum și tehnicile moderne bazate pe inteligență artificială, în special analiza imaginilor integrată cu rețele neuronale. Pe lângă prezentarea principiilor de funcționare, recenzia evaluează factorii cheie, inclusiv acuratețea măsurătorilor, reproductibilitatea, compatibilitatea probei și nivelul de procesare a datelor necesar. Instrumentele bazate pe inteligență artificială sunt evaluate în ceea ce privește capacitatea lor de a spori automatizarea, de a realiza monitorizarea în timp real și de a extrage caracteristici morfologice avansate. De asemenea, sunt abordate provocările asociate cu standardizarea metodelor, comparabilitatea datelor și implementarea lor în fluxurile de lucru industriale. Prezenta analiză are drept scop sprijinirea cercetătorilor și a inginerilor de proces în selectarea unor metode adecvate și scalabile pentru determinarea precisă a dimensiunii și formei particulelor în aplicațiile care implică pulberi de fructe de pădure.

INTRODUCTION

Berry fruit powders are recognized as valuable ingredients in both the food and pharmaceutical sectors due to their high concentrations of antioxidants, vitamins, and diverse bioactive compounds. Beyond improving the nutritional quality of formulations, they exert beneficial physiological effects, including antioxidant activity, modulation of inflammatory pathways, and enhancement of immune function. In powder form, these products offer extended shelf life, greater physicochemical stability during storage and transportation, and versatility for incorporation into a wide range of functional food and therapeutic formulations (*Nabil, B., et al, 2020).*

Physical characteristics of these powders, such as flowability, tendency to agglomerate, and mixing behavior are strongly affected by particle size and shape. Typically, larger and more rounded particles exhibit superior flowability compared to smaller or irregularly shaped ones, whereas a decrease in particle size often leads to reduced fluidity and an increased angle of repose. Considering these influences, particle size also plays a crucial role in determining the functional behavior and physicochemical stability of berry-derived powders, being significantly shaped by technological processes including size reduction, fractionation, and homogenization. Because particle size is closely related to specific surface area, it also affects the release, distribution, and bioavailability of macronutrients and bioactive compounds, factors essential for optimizing the nutritional value and functional performance of these powders in food and nutraceutical applications. (*Nabil, B., et al, 2020; Camacho, M., et al, 2020; Iztayev, A., et al, 2024*). Moreover, ground and sieved particles may exhibit distinct functional properties, such as water-holding capacity and the controlled release of chemical compounds during processing. The distribution of macronutrients and bioactive compounds including proteins, carbohydrates, vitamins, and polyphenols can vary significantly across particle size fractions. Finer particles are generally enriched in soluble and bioactive components, whereas coarser fractions tend to retain higher levels of insoluble dietary fiber and vitamins (*Decanal, G.C., 2024; Ionescu, A.D., et al, 2024; Baldelli, A., & Aguilera, J. M., 2025; Aziz, M. G., et al, 2018*).

The role of particle size is increasingly recognized as a critical factor influencing both the efficiency of extraction and the accurate evaluation of bioactive compounds in plant-based materials. In the case of berry powders, which are highly valued for their rich phytochemical profiles and potential therapeutic effects, variations in particle size can significantly impact analytical results. Insufficient control or reporting of particle size distribution may lead to inconsistencies in the quantification of bioactive compounds, potentially distorting interpretations regarding their health benefits. Implementing standardized protocols for particle size characterization could enhance the reproducibility and reliability of analytical data, ultimately contributing to a more robust understanding of the functional potential of compounds derived from berry powders. Accurate determination of particle size distribution is fundamental for berry powders, given its direct impact on the precise quantification of bioactive compounds and the reproducibility of their functional effects (*Baldelli, A., & Aguilera, J. M., 2025)*. Although conventional techniques such as mechanical sieving or laser diffraction are commonly employed for this purpose, they often fail to fully capture the complexity and heterogeneity of plant-based powders. Consequently, advanced methods incorporating artificial intelligence (AI), including image-based particle analysis, machine learning classification, and predictive modeling have been increasingly adopted to enhance particle characterization and ensure more reliable analytical outcomes (*Nalluri, V. R., 2011*).

În practice, the determination of particle size is inherently complex, particularly when the analysis involves a large number of irregularly shaped particles. To enable meaningful interpretation and cross-comparison of results obtained through different techniques, particle dimensions are commonly expressed using representative parameters, among which equivalent spherical diameters are the most widely applied. These diameters reduce the geometric and physical characteristics of individual particles into a single measurable value. Their definition is intrinsically linked to the underlying principle of the measurement method, with each technique yielding a specific form of equivalent diameter (*Höving, S., et al, 2023; Nalluri, V. R., 2011).* Thus, sieve analysis reports particle size in terms of the sieve diameter, defined as the diameter of the hypothetical sphere capable of passing through the same aperture as the investigated particle. Sedimentation-based methods determine the sedimentation diameter, corresponding to the sphere with the same terminal settling velocity in a fluid medium as the real particle. Optical techniques employing light obscuration detectors express size in terms of the projected diameter, associated with the equivalent projected area. Complementarily, laser diffraction techniques determine particle size distributions on the basis of the volume diameter, which corresponds to the dimension of an equivalent sphere having the same volume as the irregular particle, thereby expressing results in terms of equivalent particle volume (*Dodds, J.,*

2024). Figure 1 presents the most representative types of equivalent spherical diameters employed to characterize particles according to the measurement method used (*Höving, S., et al, 2023; Nalluri, V. R., 2011).*

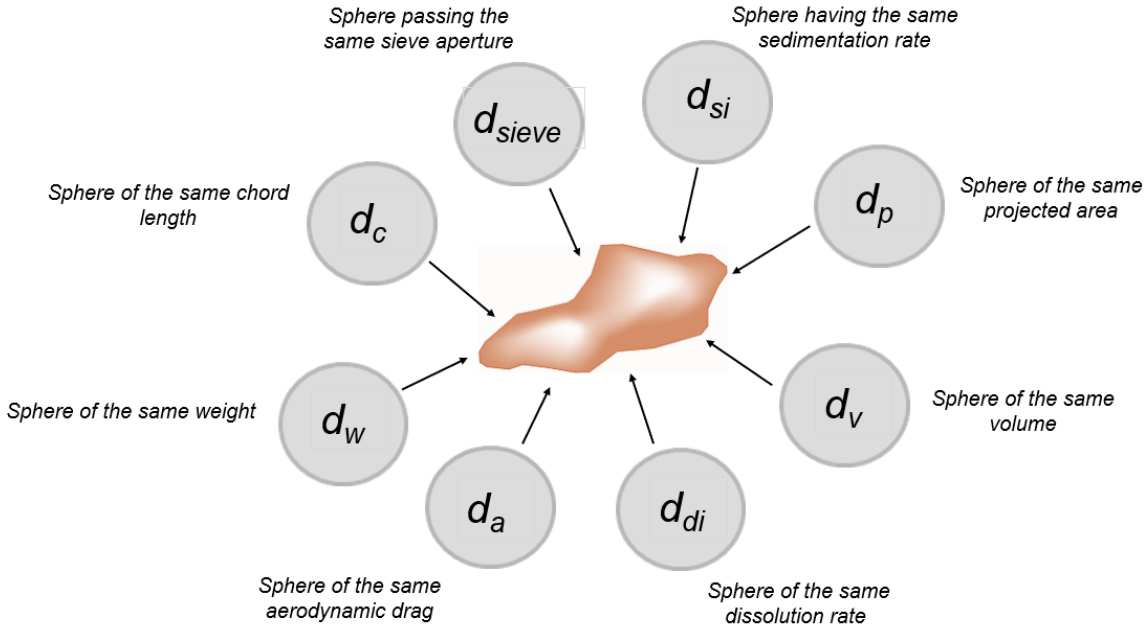

Fig. 1 - Diverse equivalent sphere interpretations based on characterization methods for irregularly shaped particles

(adapted from Nalluri, V.R., 2011)

MATERIALS AND METHODS

While a diverse array of particle characterization methodologies exists, the selection of an appropriate technique for the analysis of berry fruit powders must be critically evaluated based on material-specific properties and intended application. Berry fruit powders exhibit distinct characteristics including high hygroscopicity due to soluble sugar content, low particle density, and highly irregular morphology that directly influence the accuracy and reproducibility of size measurements.

Consequently, methods reliant on spherical or density-dependent assumptions (e.g., sedimentation, or aerodynamic separation) require rigorous calibration and validation to compensate for these inherent biases. In contrast, sieve analysis, though empirically straightforward provides a robust, practical, and economically viable approach that correlates strongly with industrial handling processes such as mixing, flow, and dissolution. Therefore, methodological selection should be guided not merely by theoretical performance but by a holistic assessment of the powder's physicochemical behavior and functional requirements in final product formulations.

1. Conventional methods for determining particle size distribution

- **Particle size distribution by analytical sieving**

Sieve analysis is one of the oldest methods for determining particle size distribution, yet it remains a standard and highly practical laboratory procedure. This technique relies on using a series of sieves with different mesh sizes. In standard laboratory practice, 200 mm diameter sieves with woven wire mesh bottoms are employed, covering an aperture range from 20 μm to 1 mm and above, in accordance with the International Organization for Standardization (ISO) specifications. All standards for sieve design are based on a geometric progression of mesh sizes.

For ISO sieves, the aperture sizes increase by a multiplying factor of √2 (approximately 1.414), providing a consistent and standardized sequence of sieve apertures. The standard analytical method involves stacking sieves in order of decreasing aperture size, placing the sample on the top sieve, and subjecting the stack to a controlled vibratory motion.The material retained on each sieve is weighed to determine the weight percentage within each size range. For berry powder, typically used in formulations where most particles are larger than 300 μm, the particle size is defined by the side length of the smallest square aperture that the particle can pass through. (*Dodds, J., 2024; Krawczykowski, D., 2024*).

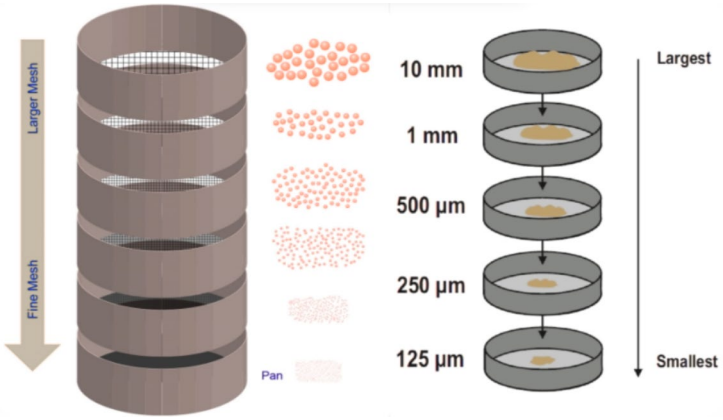

Fig. 2 - Particle size distribution by sieve analysis, principle of sequential size-based separation
(*https://www.dahanmachine.com/news-center/What-does-a-sieve-analysis-tell-you.html*)

- **Particle size analysis by laser diffraction**

In the pharmaceutical industry that employs berry fruit powders, laser diffraction (LD) particle size analysis is among the most widely applied techniques, particularly within quality control laboratories (*Nalluri, V. R. 2011*). This technique provides a broad dynamic range and high flexibility, enabling direct analysis of powders obtained from dried fruits (*Bittelli, M., et al, 2022; Ransmark, E., et al, 2025*). Laser diffraction (LD) algorithms are derived from either Mie or Fraunhofer scattering theory. The Fraunhofer approach can be viewed as a simplification of Mie theory, as it considers only diffraction, whereas Mie theory accounts for diffraction, reflection, refraction, and light absorption; consequently, the Fraunhofer model assumes that particles are opaque. Both Mie and Fraunhofer scattering theories presume that particles are spherical and isotropic, with variations in light scattering attributed only to particle size (*Ransmark, E., et al, 2025*).

Laser diffraction operates on the principle that particles within a sample scatter incident laser light at angles dependent on their size. When the laser beam interacts with the dispersed particles, diffraction occurs. The scattering angle is inversely proportional to particle diameter: smaller particles generate wider scattering angles with greater intensity, whereas larger particles scatter light at narrower angles. By measuring the intensity of light across different angles, the particle size distribution can be calculated. This calculation relies on the refractive index of both the particles and the surrounding medium (commonly water or air). Figure 3 provides a schematic representation of the laser diffraction principle (*Sedláčková, K., et al, 2024; Polakowski, C., et al, 2021*).

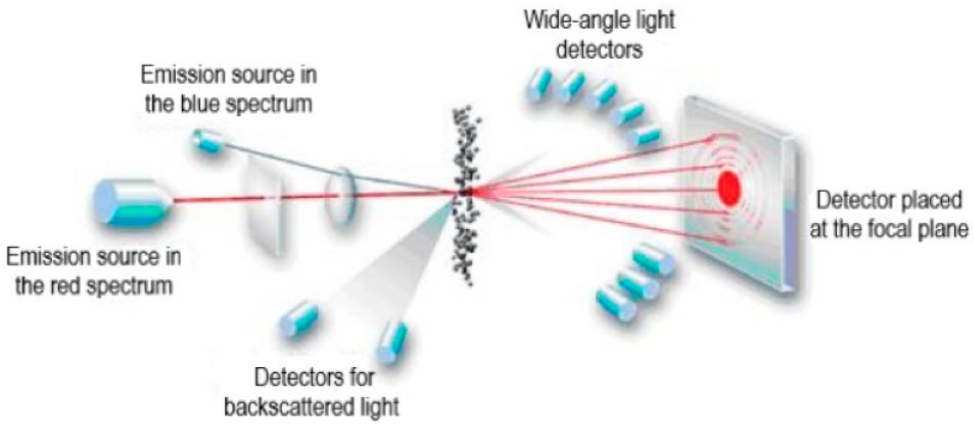

Fig. 3 - Schematic layout of a laser diffraction system for particle size analysis
(*adapted from https://www.pharmaceutical-networking.com/laser-diffraction/*)

- **Particle size estimation by microscopy**

Optical microscopy, also referred to as static image analysis (SIA), is unique among common particle sizing techniques as it allows for the direct observation and measurement of individual particles. This technique generates a two-dimensional projection of each particle for examination. Optical microscopy is typically suitable for analyzing particles measuring 1 µm or larger, with its lower detection limit being determined by the instrument's optical resolution capabilities (*Nalluri, V. R., 2011*). The projected area (A) of a particle, quantified from the pixelated outline in a digital image, serves as the most fundamental metric in

static image analysis. This two-dimensional area is conventionally reported as an equivalent circular diameter to facilitate size comparison. Another core parameter is the perimeter, typically extracted through digital erosion algorithms that computationally process the particle's contour. The Feret diameter, defined as the distance between two parallel tangents enclosing the particle profile, provides a size estimate along a specific axis. However, for non-spherical particles, this measure exhibits significant directional variability and is inherently orientation dependent. Feret diameter is measured at multiple rotation angles (e.g., every 30°). The largest and smallest values from these measurements are reported as the max and min Feret diameters While numerous methodologies exist, the most fundamental approaches utilize ratios derived from paired dimensional measurements on individual particles. Among various conceivable formulations, two common examples include: (*Dodds, J., 2024*).

$$Aspect\ ratio = \frac{Max\ Feret\ Diameter}{Min\ Feret\ Diameter} \quad (1)$$

$$Circularity = \frac{D_P}{D_A} \quad (2)$$

where:

F_{max}: Maximum Feret diameter (longest distance between two parallel tangents to the particle contour);

F_{min}: Minimum Feret diameter (shortest distance perpendicular to F_{max});

D_P: Perimeter-based equivalent diameter.

D_A: Area-based equivalent diameter.

Automated image analysis systems are divided into two main categories based on particle capture technology. The first category relies on microscope-based systems, offered by manufacturers such as Malvern (with the Morphologi G3 model) and Pax-It. These systems involve sample preparation on glass slides and dedicated software but may face limitations related to depth of field and sample representativity for larger particles. The second category consists of free-fall imaging systems, developed by manufacturers like Horiba (Camsizer series), Retsch, and Sympatec (Pictos system). These systems avoid particle orientation issues and eliminate the need for slide preparation, providing a more faithful representation of the sample. Both approaches offer automated solutions for particle characterization, each with specific advantages and limitations (*Nalluri, V. R., 2011*).

- **Particle size analysis with X-ray micro-computed tomography (µCT)**

Particle size analysis using X-ray µCT is a non-destructive method for three-dimensional characterization of berry fruit powder particles, encompassing parameters such as size, shape, and internal structure. This approach ensures robust statistical significance from a single scan (*Behnsen, J. G., et al, 2023; Gajjar, P., et al, 2020*). The methodology, summarized in Fig. 4, involves irradiating the sample with a conical X-ray beam while a detector captures transmitted radiation.

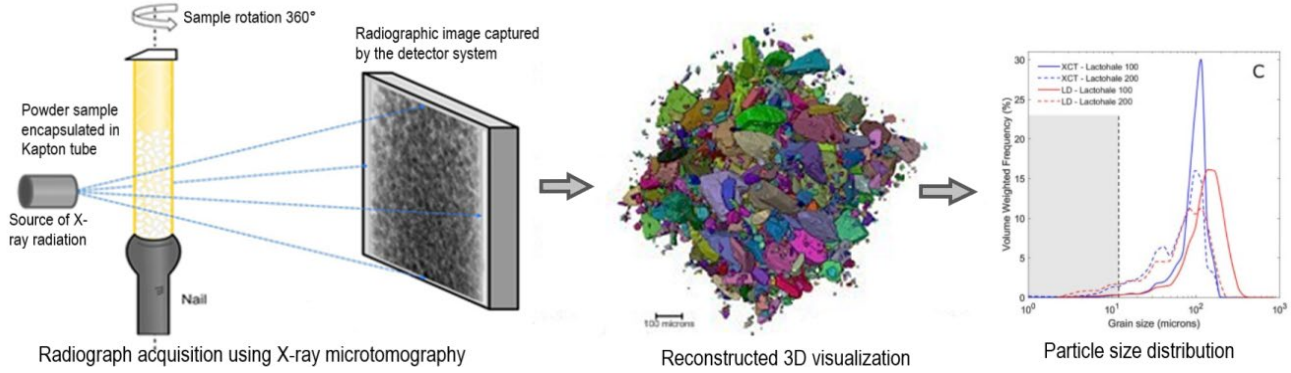

Fig. 4 - X-ray µCT- Based workflow for particle size distribution analysis of powder samples

(*adapted from Gajjar, P., et al, 2020*)

Each exposure, referred to as a projection, records the sample at a specific angular position. As the sample rotates continuously through 360°, hundreds to thousands of projections are acquired. These projections are computationally reconstructed into a 3D volume using filtered back-projection algorithms, for

example, the FDK method. The resulting volume enables detailed analysis of internal structures and extraction of particle-scale metrics. Reconstructed 3D volumes from X-ray computed tomography provide high-resolution digital representations of internal structures, facilitating direct morphological analysis of individual particles at micron-scale precision within powdered samples (*Gajjar, P., et al, 2020*).

2. AI-based methods for determining particle size distribution

Image analysis driven by artificial intelligence (AI) offers a robust and efficient alternative for determining particle size, ensuring high accuracy and reliability in measurements. The application of machine learning (ML) and deep learning (DL) algorithms to analyze particle images addresses the critical challenge of particle overlapping, which often limits the effectiveness of traditional in-line particle sizing methods. By accurately distinguishing between particles under even the most demanding conditions, AI-driven techniques eliminate the need for additional hardware components such as chromatic light arrays or atomising air systems, thereby simplifying the instrument architecture and reducing overall complexity. This simplification leads to a more compact device design, significantly broadening potential applications. A method developed by Madarász, L., et al, (2023) enables real-time particle size analysis by integrating a 6 mm endoscopic probe and a process camera with AI-based image processing software. The approach relies on capturing dynamic images of particles during processing, which are analyzed using a pre-trained deep learning model to determine size distributions. Validation is achieved through comparison with established reference methods, and the system is designed for in-line monitoring within continuous manufacturing processes. The image analysis software employs a convolutional neural network (CNN), a deep learning architecture specialized in processing visual data. CNNs excel at autonomously learning hierarchical features from images through multiple convolutional layers. Each layer applies filters to detect elementary patterns, such as edges and textures, which are progressively integrated into higher-level representations. This enables the model to accurately identify and classify particles based on their morphological characteristics without relying on manual feature engineering. To train the AI model, a dataset was constructed by extracting and manually annotating 150 images from recordings of particles in the 200–300 µm range and 120 images from the 710–1000 µm range. Fig. 5 schematically illustrates the in-line experimental setup developed in this study. The imaging system was integrated directly onto a continuous oscillatory mill, enabling real-time particle size analysis at the process outlet (*Madarász, L., et al, 2023*).

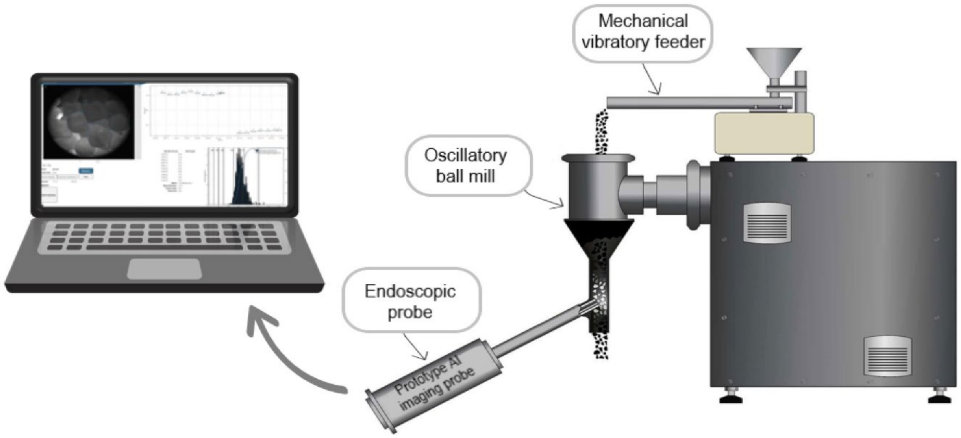

Fig. 5 - Schematic representation of the in-line monitoring system integrated with a continuous oscillatory mill for real-time particle size analysis.
(*adapted from Madarász, L., et al, 2023*)

The mill, equipped with an 800 µm screen, was operated at a defined intensity. A vibratory feeder supplied the material continuously, and a custom-designed funnel guided the particles toward the camera for imaging. Particle size distribution was computed by aggregating data from both coarse and fine fractions. For validation, reference measurements were performed using laser diffraction. (*Madarász, L., et al, 2023*).

Przybył, K. et al. (2025) prepared blackcurrant powder samples for SEM analysis by attaching them with double-sided tape and sputtering with gold. SEM images were acquired at 500× magnification (100 µm scale), with an accelerating voltage of 12.82 kV and working distance of 10 mm, yielding 420 original TIFF images (35 per variant). These images were preprocessed using Python's PIL library: converted to JPG, cropped to 1400×1400 resolution, and augmented via 90°, 180°, and 270° rotations. A sequential CNN

model (8 layers: Conv2D, MaxPooling2D, Flatten, Dense with ReLU/sigmoid) was trained on 75% of the data (105 images/variant) using binary cross-entropy loss and the Adam optimizer. The test set contained 35 images per variant. The study designed 36 CNN variants to classify carrier proportions (30% to 50%) in blackcurrant solutions (*Przybył, K., et al, 2025*).

RESULTS

- **Comparison of conventional and AI-based method performance**

Particle size analysis of berry fruit powders demands techniques that simultaneously optimize precision, efficiency, and scalability. Conventional methods, including sieving, laser diffraction, microscopy, and X-ray μCT, remain prevalent but suffer from limitations such as prolonged processing, human intervention, or restricted resolution. This section contrasts these established techniques with emerging AI-based approaches (e.g., CNN models) across key practical metrics: measurable size range, resolution, accuracy, and operational speed. As summarized in Table 1, AI-driven approaches demonstrate a clear advantage for high-throughput, automated particle characterization.

Table 1

Comparative analysis of particle size characterization methods (*addapted from Gajjar, P., et al, 2020*)

Method	Size range	Dimensionality	Resolution	Accuracy/Error	Processing time	Key limitations
Sieving	20 μm – 20 mm	3D	>5 μm	±5%	30 min – 2 h	Operator-dependent, dry samples
Laser Diffraction	0.1 μm – 3 mm	3D	0.5 μm	±3%	5–10 min	Refractive index dependency
Microscopy (SEM)	0.5 μm – 1 mm	2D	1 μm	Subjective	1–3 h	Sample preparation, time-consuming
X-ray μCT	0.5 μm – 10 mm	3D	2.5 μm	±2%	≥2 h	Cost, complex data processing
AI-Based (CNN)	0.5 μm – 5 mm	2D/3D	<1 μm	>98% accuracy	<5 s	Large training dataset required

- **Limitations of conventional methods for berry fruit powders**

For berry fruit powders, sieving faces critical limitations due to the specific characteristics of these materials. Hygroscopic powders, such as those derived from rosehip or blackthorn, tend to agglomerate under humid conditions, leading to screen clogging and result distortion. Non-spherical particles and fibrous components in these powders are misclassified due to orientation dependence on the sieve, while the measurement of fine particles becomes unfeasible. These limitations, combined with prolonged processing times and the requirement for pre-drying, render sieving unsuitable for accurate characterization of berry fruit powders (*Ionescu, A. D., et al, 2024; Liang, C., et al, 2023*).

Laser diffraction (LD) yields inaccurate size distributions for non-spherical particles due to complex scattering signals that fail to distinguish between size and shape. The error is exacerbated in heterogeneous samples (e.g., fruit powders), where variations in refractive index and particle agglomeration cause result distortion. Pre-isolation of target particles is critical to minimize interference but does not fully eliminate the technique's fundamental limitations (*Ransmark, E., et al,* 2025).

Microscopy, while valuable for direct visual assessment of particle morphology and dispersion state, suffers from significant limitations in quantitative particle size analysis of berry fruit powders. The method is inherently low-throughput, with manual examination typically limited to a few thousand particles per day, leading to risks of non-representative sampling and operator fatigue. Furthermore, the conversion of 2D projected images to size distributions introduces subjectivity (e.g., choice of measured dimension) and amplifies errors when estimating weight-based distributions, as larger particles disproportionately influence results. Although microscopy offers high resolution, it requires elaborate sample preparation and remains impractical for quality control due to its slow throughput (*Liang, C., et al, 2023, Quilaqueo, M., et al, 2019*).

X-ray computed tomography (CT) faces inherent limitations in particle characterization. A key constraint is the dependence on X-ray transmission, which diminishes with higher atomic numbers, necessitating thinner samples for effective imaging. Furthermore, the field of view (FoV) in conventional

systems restricts the volume of material analyzable in a single scan, reducing statistical robustness. Data management challenges arise from the large file sizes generated, which strain computational resources. Additionally, image noise and artifacts complicate the accurate delineation of individual particles, particularly in complex or heterogeneous samples (*Behnsen, J. G., et al, 2023*).

- **AI-based solutions, advantages and validation**

Przybył, K. et al. developed neural models for quality assessment of spray-dried chokeberry powder, combining computer image analysis with machine learning. Their approach utilized images captured via digital cameras and electron microscopy, reduced in dimensionality using Principal Component Analysis (PCA) to enhance dataset learning efficiency. The study identified Multi-Layer Perceptron (MLP) networks as the most effective topology, achieving a classification accuracy of 0.99 and a Root Mean Square Error (RMSE) as low as 0.11. This demonstrates the high potential of MLP-based neural networks in accurately identifying key quality parameters of berry fruit powders from digital images (*Przybył, K., et al, 2019*).

Notably, the same research group proposed a novel methodology for the quality assessment of raspberry powders by integrating Scanning Electron Microscopy (SEM) with two distinct neural network architectures. The study designed Multi-Layer Perceptron Networks (MLPNs) leveraging texture descriptors for feature extraction, alongside Convolutional Neural Networks (CNNs) processing raw bitmap images to capture deep hierarchical patterns. This hybrid approach enabled high-accuracy classification of microparticle homogeneity directly from image pixel texture, demonstrating significant potential for automated quality control in berry powder production. The models achieved exceptional performance, highlighting the effectiveness of combining SEM-based structural data with machine and deep learning techniques (*Przybył, K., et al, 2021*). Four years later, the same authors expanded their approach by integrating convolutional neural networks (CNN) with low-field nuclear magnetic resonance (LF-NMR) and instrumental texture analysis to comprehensively evaluate the morphological and molecular structure of blackcurrant powders. The study used CNNs to process digital images of microparticles, extracting features such as shape, dimensions, and color space patterns to classify morphological variants. The combination of deep learning (CNN), molecular analysis (LF-NMR), and physical properties (texture) provided a multidimensional framework for quality assessment, demonstrating the synergy between advanced artificial intelligence techniques and conventional analytical methods in food science. In this study, the convolutional neural network (CNN) was designed as an eight-layer sequential model, comprising convolutional layers (Conv2D), max pooling layers (MaxPooling2D), a flattening layer, and fully connected dense layers, as illustrated in Fig. 6, to effectively process and extract relevant features from particle images (*Przybył, K., et al, 2025*).

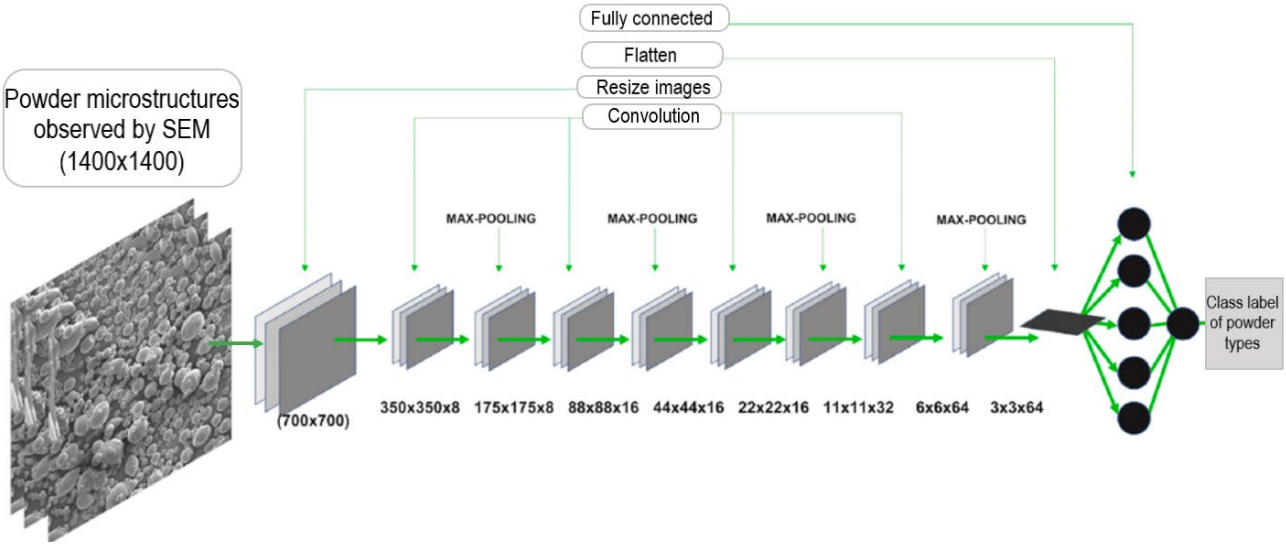

Fig. 6- Architecture of the Convolutional Neural Network (CNN) model for blackcurrant powder image analysis
(*adapted from Przybył, K., et al, 2025*)

Höving, S. et al. developed an evaluation method combining micro-computed tomography (μ-CT) and artificial intelligence to determine particle size distribution (PSD) and shape directly from bulk

samples. Unlike conventional techniques (e.g., sedimentation, laser diffraction, microscopy), this approach enabled 3D analysis of individual particles while preserving their true morphology. AI-based instance segmentation achieved high accuracy (80% detection rate) and reconstructed particles at a resolution of 8 µm voxels. The method allowed quantification of Wadell sphericity, agglomeration degree, and shape distributions, though full sphericity potential was not exhausted. Preliminary validation using a model substance confirmed feasibility, with future work aimed at extending the method to diverse particulate systems (*Höving, S., et al, 2023*).

Kálnai, Á. et al. developed an advanced real-time method for component-based particle size analysis of pharmaceutical powder blends using machine vision and artificial intelligence. The experimental setup included a twin-screw feeder (Brabender Technologie, Germany) operating at 0.12 kg/h, an inclined glass plate (45°) to maintain particle alignment, and a Basler acA4112–30uc camera (12 MP, 4096 × 3000 resolution) equipped with a 3X telecentric objective. Illumination was provided by a high-intensity fiber optic LED at 30°, ensuring optimal particle-background contrast. The system captured 812 training images and 20-second videos (10 fps) for particle size distribution analysis.The method was validated against offline microscopy, results demonstrated strong correlation between real-time measurements and reference data, confirming the system's accuracy for complex blends. Industrially, this approach is adaptable to berry fruit powder mixtures (e.g., blueberries, raspberries, or carriers like maltodextrin) for both pharmaceutical supplements and food applications. It enables inline quality control during production of capsules, granules, or tablets by linking particle size to functional properties (e.g., dissolution rate, absorption capacity) (*Kálnai, Á., et al, 2025*).

CONCLUSIONS

This study demonstrates that AI-based methods (e.g., CNN, MLP) significantly outperform conventional techniques (sieving, laser diffraction, microscopy) in the particle characterization of berry fruit powders, offering superior accuracy (>98%), real-time processing capabilities, and the ability to capture multidimensional features (morphology, texture, molecular structure). While conventional methods remain valuable for specific applications, their limitations in throughput, resolution, and subjectivity are overcome by AI-driven approaches, which enable automated, non-destructive, and high-resolution analysis. The integration of AI with advanced analytical tools (e.g., µCT, LF-NMR) provides a holistic framework for quality assessment, paving the way for future applications in pharmaceutical and food industries, where precision, scalability, and real-time monitoring are critical. Further research should focus on standardizing AI models for broader industrial adoption and addressing challenges related to training data requirements and computational resources.

ACKNOWLEDGEMENT

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APPLICATION OF GOOD AGRICULTURAL PRACTICES TO IMPROVE SOIL HEALTH IN THE CENTRAL REGION - CASE STUDY

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APLICAREA BUNELOR PRACTICI AGRICOLE PENTRU ÎMBUNĂTĂȚIREA SĂNĂTĂȚII SOLULUI ÎN REGIUNEA CENTRU - STUDIU DE CAZ

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Keywords: *soil health, ploughing, subsoilers, quality indices*

ABSTRACT

Good agricultural practice means working the soil efficiently, but also responsibly, in a way that protects its structure, fertility and biodiversity. It is not just about following rules – it is about adapting technologies and methods to real conditions on the ground. Compaction is a form of physical degradation of the soil, which has serious consequences on agricultural production, being produced also because the plowing work was carried out at the same tillage depth, when the hardpan is formed. This case study investigates the use of a reversible plow equipped with subsoilers, designed to break compacted layers and improve aeration and water infiltration, under the pedoclimatic conditions of Mureș County. The experimental plots for determining the qualitative work indices, energy indices and operational indices were located within the Ernei, Icland and Reghin localities in Mureș County, Center Region.The results obtained from the case study led to several recommendations for good practices for tillage with a reversible plow equipped with subsoilers.

REZUMAT

Buna practică agricolă înseamnă să lucrezi solul eficient, dar și responsabil, astfel încât să protejezi structura, fertilitatea și biodiversitatea acestuia. Nu este vorba doar despre respectarea unor reguli – ci despre adaptarea tehnologiilor și metodelor la condițiile reale din teren. Compactarea este o formă de degradare fizică a solului, care are consecințe grave asupra producției agricole, fiind produsă și pentru că lucrările de arat s-au efectuat la aceeași adâncime, unde s-a format hardpanul. Acest studiu de caz investighează utilizarea unui plug reversibil echipat cu scormonitori, conceput pentru spargerea straturilor compactate și îmbunătățirea aerării și infiltrației apei, în condițiile pedoclimatice ale județului Mureș. Loturile experimentale pentru determinarea indicilor calitativi de lucru, a indicilor energetici și a indicilor de exploatare au fost situate pe raza localităților Ernei, Icland si Reghin din județul Mureș, Regiunea Centru. Rezultatele obtinute in urma studiului de caz au condus la cateva recomandări de bune practici pentru lucrarea solului cu plugul reversibil echipat cu scormonitori.

INTRODUCTION

The concept of soil health has emerged as a fundamental pillar in the pursuit of sustainable agriculture (*Grover, D. et al, 2024*). Conventional agricultural systems such as the use of chemical fertilizers, mechanical tillage, and irrigation, although increasing crop production, cause soil erosion, loss of biodiversity, and decline in soil structure and soil organic matter (*Alori, E. T. et al, 2020*).

Tillage practices affect soil chemical and physical properties, as well as fruit quality and crop yield as reported in watermelon and rice-maize cropping systems (*Sahu, P. et al, 2019; Gathala, M.K. et al, 2015*). Farming practices have shown that organic farming and tillage improve soil health by increasing the abundance, diversity, and activity of microorganisms (*Tahat, M. M. et al, 2020*).

Ploughing is a fundamental agricultural operation for preparing the seedbed and maintaining soil health, having a direct impact on crop productivity (*Smith & Johnson, 2017*). Plowing loosens and aerates the arable layer, incorporates plant residues, destroys weeds and stimulates biological processes beneficial to the soil (*Steponavičienė, V. et al*, 2023). From the perspective of the specialized literature, the use of ploughs equipped with subsoilers offers a series of technological and agrotechnical advantages that contribute to improving the quality of soil work (*Havlik & Novak, 2016*).

Compaction is a form of physical degradation of the soil, which has serious consequences on agricultural production, being produced also because the plowing work was carried out at the same tillage depth, when the hardpan is formed (below the plowing level there is a layer more compact) (*Nawaz, M.M. et al, 2023*). Evaluating the effectiveness of mechanical soil loosening to reduce subsoil compaction is a complex challenge, as the stresses to which the active parts of agricultural machinery are subjected depend on variable factors such as soil texture, moisture, working depth and travel speed (*Seehusen, T. 2025*).

In many areas of central Romania, intensive farming practices and the use of heavy machinery have led to soil compaction, reduced porosity, and degradation of its physical and biological properties (*Rusu, T. et al, 2025*). Implementing Good Agricultural Practices, focused on conservation tillage and improving soil structure, is increasingly necessary to maintain fertility and water balance.

This case study investigates the use of a reversible plow equipped with subsoilers, designed to break compacted layers and improve aeration and water infiltration, under the pedoclimatic conditions of Mureș County. The main objective was to evaluate the technical, energy, and operational performance of this system, as well as its effects on soil health. By integrating modern equipment within good agricultural practices, this research contributes to the development of sustainable soil management solutions in conventional farming systems.

MATERIALS AND METHODS

This case study was conducted using a reversible plow with shares equipped with subsoilers, used for primary tillage to mobilize the soil, break compacted layers, and improve the water regime.

The experimental plot for determining the qualitative work indices and energy indices was located within the Ernei locality in Mureș County, Center Region (Figure 1). From a thermal point of view, the area is characterized by an estimated average annual temperature between 8.7°C and 10.1°C and an average annual amount of precipitation that varies between 563.1 mm and 650 mm. The experimental plot, which is located in an area with hydrological influence (close to the Mureș River), has a clay-luvial podzolic soil type, which is heavy and sticky due to the high clay content, which made the moisture stay in the soil longer.

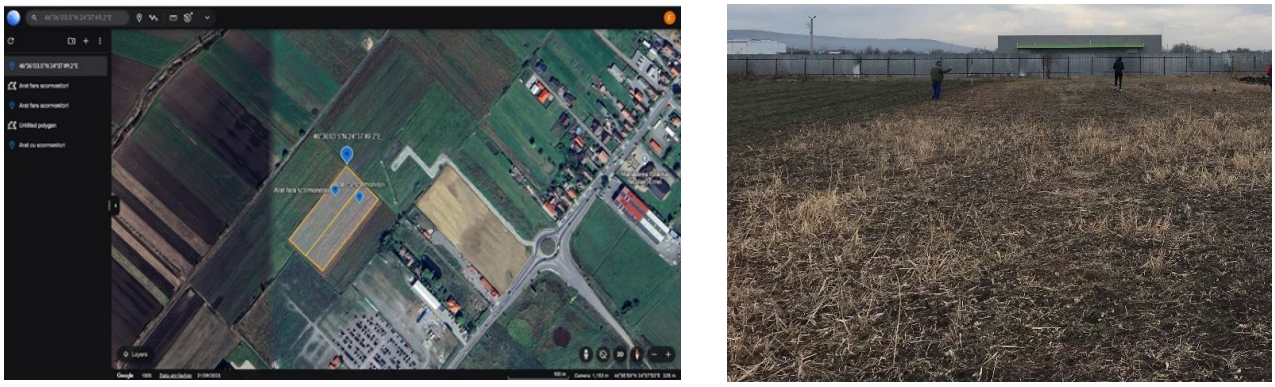


Fig. 1 - Location and real image of the Ernei experimental plot

Measurements were performed in three repetitions for each experimental variant. Work quality indices (depth, width, residue coverage, soil crumbling) and energy indices (speed, traction force, slippage, draft power, working capacity, and fuel consumption) were recorded. Data were statistically processed to calculate mean values and percentage variations.

The operational indices were determined on two experimental plots in the Center Region, located in the Icland (Figure 2) and Reghin (Figure 3) locations. The following operational indices were determined: effective working capacity, fuel consumption, exploitation coefficients K02 (operating time coefficient), Kprod (production coefficient), and K07 (exchange time coefficient).

The soil in the experimental plot located at the Icland location is reddish-brown forest type, and the soil in the experimental plot located at the Reghin location is fertile alluvial soil.

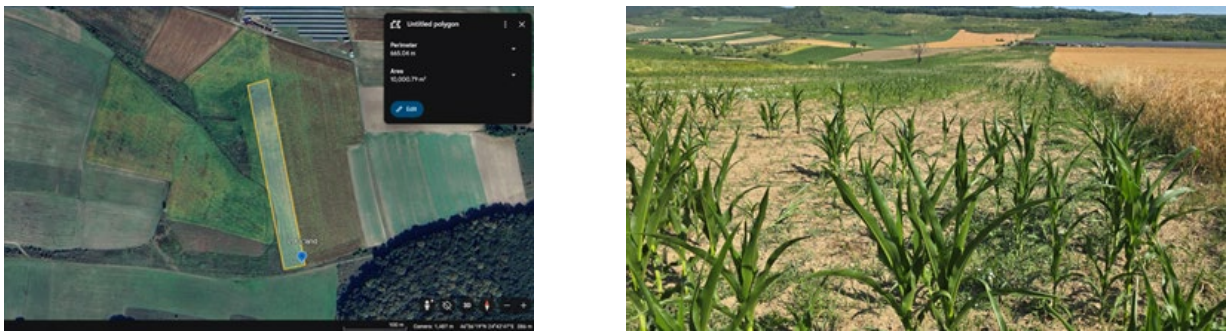


Fig. 2 - Location and real image of the Icland experimental plot

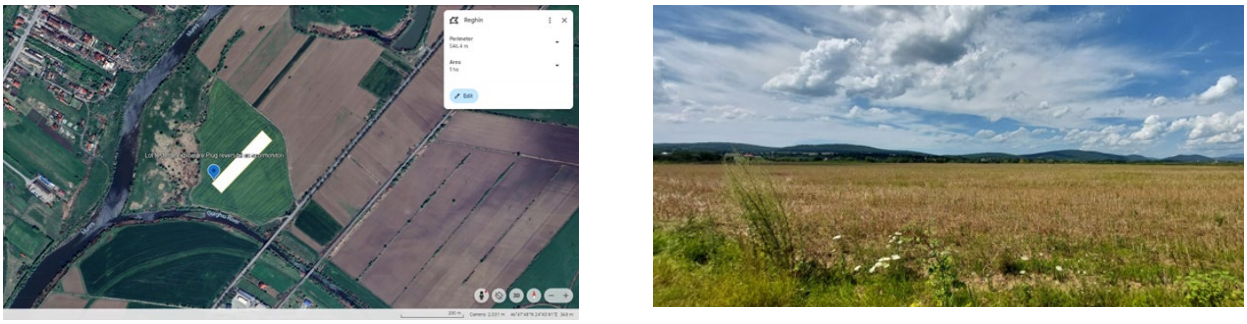


Fig. 3 - Location and real image of the Reghin experimental plot

The three-share reversible plow with subsoilers was used in combination with the TAGRO 102 IRUM tractor (102 HP). Measurements highlighted the influence of soil moisture and compaction on machinery performance.

RESULTS

The working conditions for determining the qualitative work indices and energy indices in the experimental plot in Ernei, Mures County (Figure 4) were: heavy, sticky podzolic clay-loam soil, moisture ~23%, penetration resistance 1370–1400 kPa.

Staking out the experimental plot

Recording experimental data to determine working speed, slippage and traction force

The plot aspect after the experiments were carried out

Fig. 4 - Aspects during the determination of work quality indices and energy indices in the experimental plot in the Ernei location, Mures County

Table 1

Results obtained when determining the average working depth and width of the reversible plough

Repetition	a_m [cm]	S_a [cm]	V_a [%]	B_m [cm]	S_B [cm]	V_B [%]
1	25.4	2.37	9.03	100.2	7.37	6.95
2	24.8			104.8		
3	28.6			112.4		
Average	**26.27**			**107.8**		

where:

- a_m is the average working depth, cm;
- S_a - the root mean square deviation of the working depth;
- V_a - the working depth variation index, in %;
- B_m - the average working width, cm;
- S_B - the root mean square deviation of the working width;
- V_B - the working width variation index, in %.

From the analysis of the results presented in Table 1, it was found that the variation in working depth and width falls within the limit of maximum 10%, resulting in high uniformity.

Table 2

Degree of coverage of plant residues (G_v)

Average working depth [mm]	Working speed [m/s]	Plant residues [kg/m²]		
		Sample 1	Sample 2	Sample 3
26.27	1.23	0.05	0.06	0.08
		G_v (%)		
		9.09	10.91	14.55

The total mass of plant residues was on average: 0.55 kg/m2 (Table 2).

A plant residue mass of 0.05...0.08 kg/m² suggests a small amount of plant material remaining on the soil surface after harvest, resulting in good incorporation.

Table 3

Degree of soil fragmentation (G_m)

Average working depth [mm]	Working speed [m/s]	Sieve 1 100 mm [kg]	Sieve 2 50 mm [kg]	Sieve 3 25 mm [kg]	Smaller than 25 mm [kg]
26.27	1.23	108.8 (9.,67%)	1.65 (1.48%)	0.45 (0.40%)	0.5 (0.45%)

The weighings were carried out using a 0-350 kg scale with an allowable error of 50 g, and for the separation of soil fractions, sieve sets with round holes were used, with hole diameters of 100, 50 and 25 mm (Table 3).

The fraction weight ratio indicates the degree of fragmentation of the soil and helps to understand its physicochemical properties, such as permeability, water holding capacity, and nutrient holding capacity. A soil with a high fraction of fine particles will have a higher water holding capacity but will have a low permeability, while a soil with more coarse particles will be better drained. Given that fragments larger than 100 mm account for 94.67%, it is indicated that the soil mainly contains very large particles, suggesting that the soil is predominantly coarse.

This soil is well-drained, aerated, but with a low water and nutrient retention capacity, requiring careful management of irrigation and fertilization to support plant growth.

The energy indices were determined for two working options. The experimental variant V1 was when the reversible plough with three furrows without subsoilers was used, and the experimental variant V2 was when the reversible plough with three furrows with subsoilers was used (Table 4).

Table 4

The results obtained when determining working speed, traction force, slippage and traction power

Variant	Working depth of the plough [cm]	Working depth of the subsoiler [cm]	Working speed [m/s]	Traction force [daN]	Tractor slippage [%]		Traction power [CP]
V1	25	15	1.53	3289	25.67	28.19	67.10
V2	25	15	1.25	3390	28.19	31.96	56.50
V1	25	20	1.44	3879	25.67	25.67	74.48
V2	25	20	1.29	4006	25.67	33.21	68.90
V1	25	0	1.52	2614	25.67	24.42	52.98
V2	25	0	1.23	2815	28.19	30.70	46.17

Reducing the plowing depth from 30 cm to 25 cm, adjusting the tire pressure and adding additional weights was done to reduce the tractor's slippage (slipping) during plowing, which is an important indicator of traction efficiency. Under these conditions, a maximum speed of 1.53 m/s (5.5 km/h) was achieved, which is generally an acceptable value for plowing work, given the soil type, terrain conditions and adjustments made to the plow.

Due to the high soil moisture (22.9% in the 0-20 cm layer and 23.16% in the 21-40 cm layer) and excessive tractor slippage (maximum was 33.21% and minimum was 25.67%), plowing under these conditions is not efficient. The optimal slippage level should be below 20% to ensure adequate traction, low fuel consumption and minimal equipment wear.

The experimental plot was located in an area with hydrological influence, near the Mureș River, on a clay-luvial podzolic soil, characterized by: high clay content (heavy and sticky soil); high water retention capacity (humidity remains high for a long period after precipitation); high penetration resistance (≈ 1370–1400 kPa, indicating a moderate to high degree of compactness).

It is clear from Figure 1 that the ploughing was done on a very wet, heavy and plastic soil. The furrows are large, irregular and with a shiny surface, a sign that the soil stuck to the tiller and did not crumble well. The edge of the furrow is well outlined, but the sticking indicates resistance to progress and, implicitly, higher fuel consumption. It is visible that the soil was worked in unsuitable conditions for optimal energy efficiency.

Table 5

Comparison of experimental variants

Indicator	Without Subsoiler (V1)	With Subsoiler (V2)	Difference
Working speed	1.50 m/s	1.26 m/s	↓ 16%
Traction force	2927–3879 daN	2815–4006 daN	+3–7%
Slippage	25.7%	28–33%	+2.5–7.5 pp
Draft power	53–74 HP	46–69 HP	-6–10 HP
Working capacity	0.452 ha/h	0.474 ha/h	+4.8%
Fuel consumption	41.2 l/ha	50 l/ha	+21%

Although soil moisture was moderate (~23%), the clayey and sticky texture meant that the retained water did not reduce resistance, but increased friction and soil sticking to the working tools. Spot moisture was not the main factor in consumption, but soil type and degree of compaction.

The installation of the subsoilers increased the volume of soil mobilized and the contact surface, leading to increased traction force, slippage and fuel consumption. In heavy and wet soils, this effect is amplified.

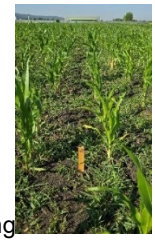
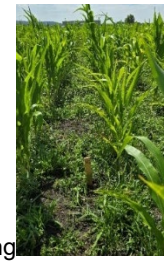
From an energy efficiency point of view, variant V2 had a consumption ≈ 21% higher than variant V1, although the working capacity increased by only ≈ 4.8% (Table 5).

A corn crop was subsequently established on the experimental plot in the Ernei location, which was monitored over time by measuring the following parameters: germination percentage, average plant height, average number of active leaves/plant and leaf condition (Table 6).

Table 6

Results obtained from corn crop monitoring, comparing variant V1 versus V2

Calendar date	Parameter	Ploughing without subsoilers (V1)	Ploughing with subsoilers (V2)
July 08, 2025	Germination percentage	73 % (11 plants/m²)	88 % (14 plants/m²)
	Average plant height	63 cm	87 cm
	Average number of active leaves / plant	9 leaves (some yellowed)	11 leaves (some yellowed)

Calendar date	Parameter	Ploughing without subsoilers (V1)	Ploughing with subsoilers (V2)
	Leaf condition	Light stains and yellowing	Light stains and yellowing 
July 22, 2025	Germination percentage	73 % (11 plants/m²)	88 % (14 plants/m²)
	Average plant height	85 cm	120 cm
	Average number of active leaves / plant	11 leaves (some yellowed)	15 leaves (some yellowed)
	Leaf condition	Light stains and yellowing	Light stains and yellowing 

From Table 6 it can be seen that working with plow mounted subsoilers had the following effects on the corn crop: emergence 88% vs 73%; average plant height 120 cm vs 85 cm; active leaves: 15 vs 11. At the same time, subsoilers improve crop development but increase energy consumption.

The operational indices (Table 7) were determined in the experimental plot from Icland location, Mureș County with reddish-brown forest soil, moisture 10%, penetration resistance 340 psi.

Table 7

Analysis of operational indices determined in the experimental plot from Icland location, Mureș County

Indicator	Meaning	Value	Interpretation
Wef	Effective hourly capacity	0.40 ha/h	Shows working speed under ideal conditions
W04	Capacity at production time (with technical times)	0.29 ha/h	Real efficiency including setup and repair times
W07	Full shift capacity	0.22 ha/h	Includes breaks, maintenance, all interruptions
q	Specific fuel consumption	46 l/ha	It is a high consumption, explainable by the difficulty of the terrain
K02	Operational time coefficient	0.74	74% of operational time was effectively used – good efficiency
Kprod	Production coefficient	0.64	64% of total technology time was productive – room for improvement
K07	Exchange time coefficient	0.56	Only 56% of the time a shift was actually profitable – influenced by failures

The plough has an effective hourly capacity of 0.4 ha/h, which drops to 0.22 ha/h when the entire shift duration is taken into account. This suggests a significant loss of time due to breaks, turns and minor breakdowns.

Fuel consumption was high, indicating either increased soil resistance or non-optimized plow adjustment. The analysis of fuel consumption (hourly consumption, consumption during actual working time - ideal, consumption during fault-free time - useful) in different scenarios is presented in Figure 5.

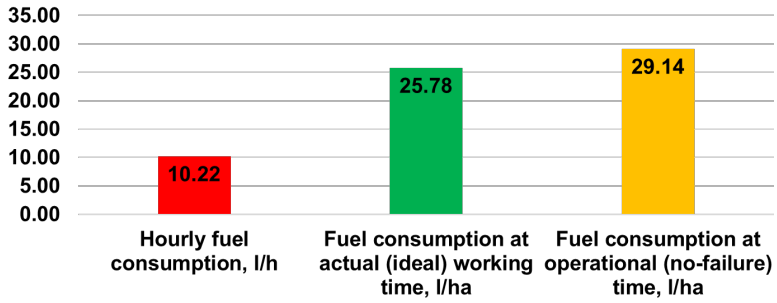


Fig. 5 - Analysis of fuel consumption in different scenarios at Icland location

The operational indices determined in the experimental plot from Reghin location, Mureș County with fertile alluvial soil, moisture 19.5%, penetration resistance < 300 psi are presented in Table 8.

Pedological evaluation at the time of the work:

- Soil moisture at 10 cm depth: 19.5%, ideal moisture for plowing, without clod formation;
- Soil compaction: up to 30 cm depth <200 psi and at a depth of 30 cm >300 psi (considered a problematic level of compaction, especially for plants with deep root systems (e.g. corn, sunflower).

Table 8

Analysis of operational indices determined in the experimental plot from Reghin location, Mureș County

Indicator	Value	Interpretation
Wef	0,55 ha/h	Effective productivity
W04	0,44 ha/h	Productivity including auxiliary times
W07	0,38 ha/h	Overall productivity (includes all interruptions)
q	31.5 l/ha	It is a high consumption, explainable by the difficulty of the terrain
K02	0,80	Efficiency of use without adjustments and malfunctions
Kprod	0,69	Overall productive efficiency
K07	0,69	Efficiency relative to total time

Kprod and K02 coefficients below 0.70 indicate a suboptimal use of available time. For example, 31% of time is lost on unproductive activities, a significant part of which is generated by mechanical failures (blocking of the depth wheel).

The test results highlighted a promising technological potential of the three-furrow reversible plow equipped with subsoilers, but a series of limitations related to non-productive times and high specific fuel consumption were also identified.

The analysis of fuel consumption (hourly consumption, consumption during actual working time - ideal, consumption during fault-free time - useful) in different scenarios is presented in figure 6.

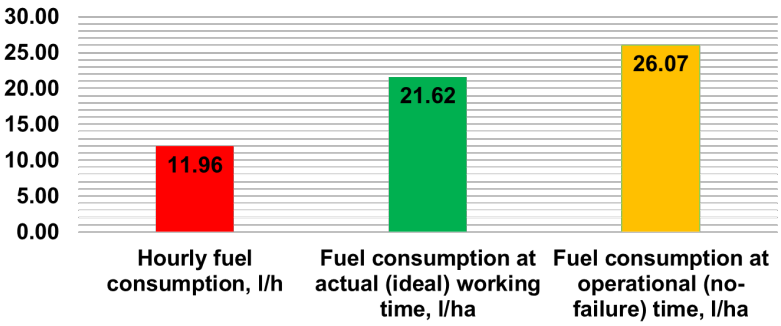


Fig. 6 - Analysis of fuel consumption in different scenarios at Reghin location

Good practice recommendations:

- Optimal timing: work with subsoilers is recommended at moderate humidity (approx. 15–20% for clay soils), avoiding both excessive drying and high humidity;

- Adjustment of subsoilers depth: the optimal depth should be adjusted according to the soil texture; in heavy and wet soils, reducing the depth by 3–5 cm can prevent an excessive increase in resistance;
- Control of slippage: it is recommended to monitor tractor slippage and, if it exceeds 15–20%, adjust ballasting, tire pressure or reduce working depth;
- Correlation of speed with tractor power: with increased resistance, the speed should be reduced to avoid engine overload and sudden increase in specific consumption.

CONCLUSIONS

Subsoilers increase fuel consumption and traction force but improve soil structure and crop development.

Optimal efficiency is achieved by adapting working depth and settings to soil type.

Heavy and wet soils (Icland and Ernei locations) require careful moisture management, while alluvial soils (Reghin location) offer superior performance and lower consumption.

ACKNOWLEDGEMENT

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GRINDING INFLUENCE IN OPTIMIZING PRODUCTION OF CONCENTRATED FEED FROM LEGUMINOUS PLANTS

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INFLUENȚA MĂCINĂRII ÎN OPTIMIZAREA PRODUCȚIEI DE FURAJE CONCENTRATE DIN PLANTE LEGUMINOASE

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Keywords: *animal food, mixing, technology, recipe, processing.*

ABSTRACT

Nutrition plays a critical role in unlocking the genetic potential of livestock, directly impacting the quality and efficiency of animal production. To develop diverse and nutritionally complete feed formulations, precise processing and preparation of feeds are essential. Producing high-quality concentrated feeds demands advanced technologies and equipment, enabling on-farm production of varied combined feeds that meet global efficiency and quality standards. Given the pivotal role of nutrition in animal husbandry, a scientific approach to livestock rearing relies heavily on rational feeding practices. These practices, in turn, depend on a robust forage base, directing efforts toward optimizing feed production. A key factor in this process is the grinding of concentrated feed components. This study explores the theoretical and experimental factors influencing the grinding process in feed formulation.

REZUMAT

Nutriția joacă un rol esențial în deblocarea potențialului genetic al animalelor, având un impact direct asupra calității și eficienței producției de carne. Pentru a dezvolta formulări de hrană diverse și complete din punct de vedere nutrițional, este esențială prelucrarea și prepararea precisă a furajelor. Producerea de furaje concentrate de înaltă calitate necesită tehnologii și echipamente avansate, permițând producția la fermă a unor furaje combinate variate care să îndeplinească standardele globale de eficiență și calitate. Având în vedere rolul esențial al nutriției în creșterea animalelor, o abordare științifică a creșterii animalelor se bazează în mare măsură pe practici raționale de hrănire. Aceste practici, la rândul lor, depind de o bază robustă de furaje, direcționând eforturile către optimizarea producției de furaje. Un factor cheie în acest proces este măcinarea componentelor concentrate ale furajelor. Acest studiu explorează factorii teoretici și experimentali care influențează procesul de măcinare în formularea furajelor.

INTRODUCTION

Nutrition is a cornerstone in maximizing the genetic potential of livestock, directly affecting the quality and efficiency of animal production. To create diverse and nutritionally balanced feed formulations, precise processing and preparation of feeds are critical. The production of high-quality concentrated feeds requires advanced technologies and equipment, enabling on-farm production of varied combined feeds that meet global standards for efficiency and quality.

Given the central role of nutrition in animal husbandry, a scientific approach to livestock rearing hinges on rational feeding practices, which rely on a robust forage base. Leguminous plants, such clover, and soybeans, are vital in fodder nutrition due to their high protein content, which supports animal growth and productivity. These plants are rich in essential amino acids, enhancing the nutritional value of feeds (*Ben Salem et al., 2008; Păun et al., 2018*).

Additionally, legumes contribute to sustainable farming by fixing nitrogen in the soil, reducing the need for synthetic fertilizers. Their high fiber content aids in digestive health, while their palatability encourages feed intake (*Păun & Stroescu, 2018; Păun et al., 2019*).

Legumes also provide vitamins and minerals, such as calcium and phosphorus, crucial for bone development and metabolic functions. Incorporating leguminous plants into feed recipes improves feed efficiency and reduces production costs. Moreover, their adaptability to various climates makes them a

reliable forage source. The grinding process is a key factor in optimizing the use of leguminous plants in concentrated feeds. This study investigates the theoretical and experimental factors influencing the grinding process in feed formulation (*Karimirad et al., 2020*).

The increase of animal stocks and the enhancement of their production are significantly conditioned by the way in which feed is provided (*Voicea et al., 2024; Tăbărașu et al., 2024*).

Rational feeding of all animal species and categories involves a harmonious combination of physiological and economic principles, which requires a thorough knowledge of two basic categories of issues, namely:

- the requirements of the animal organism regarding the content of nutrients on which the technique of setting standards and formulating feed rations is based;
- the elements that serve as a source of food, namely the feeds, in terms of their nutritional value, how they are obtained, their characteristics, and the technology of conservation, preparation, and use.

Increasing animal production is directly linked to complete nutrition at a low-cost level and occupies an important place in the agricultural sector of our country. Animal nutrition is currently perceived as a field with multiple connections to biological sciences and with a share of approximately 60–70% in the production cost of animal products (*Păun et al., 2014; Ben Salem et al., 2008*).

Processing and preparing feed are performed with the purpose of increasing the nutritional value of the feed, enhancing its palatability and digestibility, and creating a wide and complete variety of feed formulas needed in the diet of domestic animals (*Oprescu et al., 2023; Cujbescu et al., 2023*). By applying various preparation methods to feeds, we favorably modify their physical, chemical, and biological properties, which results in a better utilization of them by animals during feeding.

Feed processing is also necessary because some feeds contain various impurities (ferrous bodies, soil residues, etc.) resulting mainly from harvesting processes, which must be removed before they are administered to animals.

It is known that few feeds, in their natural state, meet all the requirements of the animal organism; therefore, they must be processed before consumption according to a specific technology.

Processing feeds from cereal seeds using different technologies is necessary because (*Tudora et al., 2024; Vlăduț et al., 2023*):

- few feeds, in their natural state, meet all the requirements of the animal organism;
- through various processing methods we favorably modify their physical (form, structure, granulation), chemical, and biological properties;
- it leads to increased nutritional value, a higher degree of digestibility, and better utilization by animals;
- it allows and facilitates the mechanization and automation of feed preparation and distribution to animals;
- it enables the production of varied and complete feed formulas according to the needs of the livestock operation;
- it ensures the removal of impurities (ferrous bodies, soil residues, etc.) from feed before administering it to animals;
- it ensures a rational use of the existing feed base on the farm for feeding animals and birds.

Knowing the importance of food as a determining factor in harnessing the genetic potential of animals—its content directly influencing the quality and efficiency of livestock production—feed processing and preparation is necessary to produce varied and complete feed formulas (figure 1).

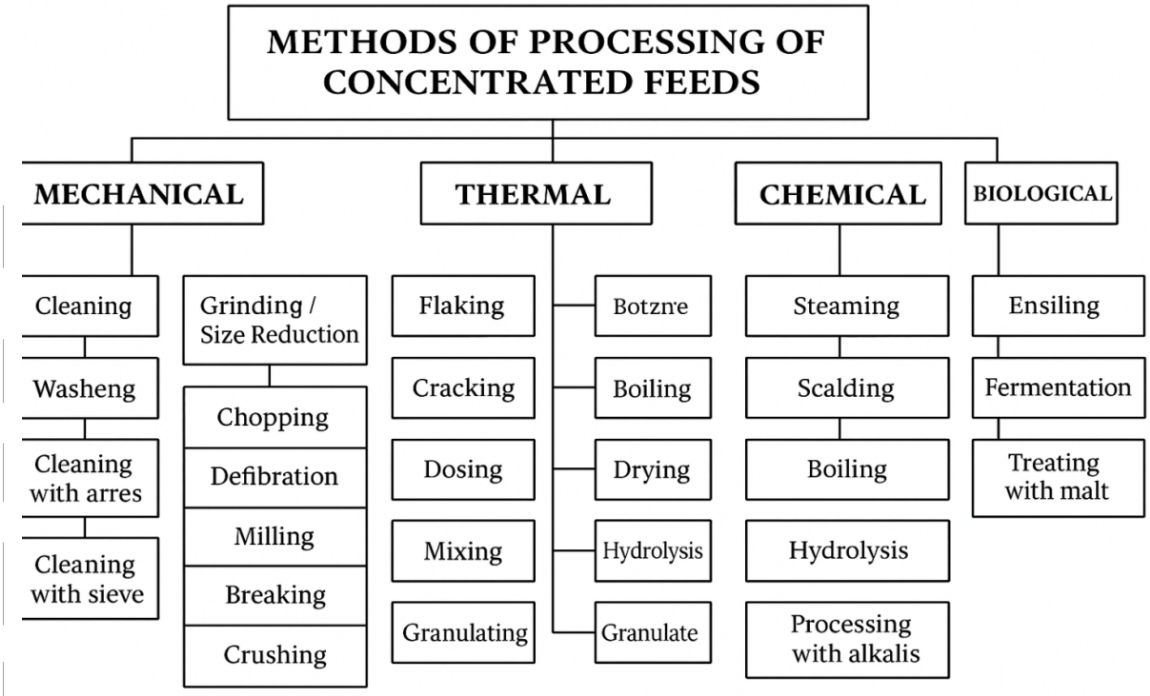


Fig. 1 - Concentrated feeds processing methods

(Ben Salem et al., 2008)

Within the concentrated feed processing technologies, a wide range of machines is used, starting with the simplest ones, which perform a single operation, and ending with complex equipment that performs several technological operations.

Starting from the technologies presented in Figure 2 and taking into account the auxiliary operations within a technology such as: interphase transport, aspiration of polluting noxious gases, etc., we will present several models of concentrated feed production technologies for different capacities.

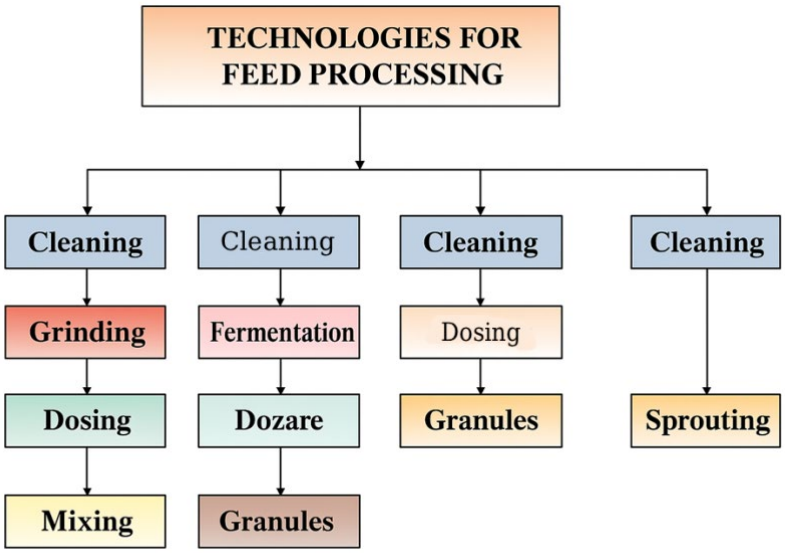


Fig. 2 - General outline of concentrated feed processing technologies

(Cujbescu et al., 2023)

Within the technologies for processing concentrated feeds, a wide range of machines is used, starting with the simplest ones that perform a single operation and ending with complex equipment that carries out several technological operations. Based on the technologies presented in Figure 2, and also taking into account auxiliary operations within a technology such as interphase transport, suction of polluting noxious substances, etc., we will present below several models of technologies for obtaining concentrated feeds for different capacities.

Obtaining satisfactory results in animal husbandry depends largely on the use of good-quality feed, the functional quality of equipment and production and processing facilities, and the quality of staff involved in the production process. Among the products intended for animal feed, concentrates occupy a special place. Concentrated feeds are characterized by a high net energy content (FUM – net energy value, expressed in “feed unit milk”; FUM – net energy value, expressed in “feed unit meat”), per kilogram of dry matter.

The grinding of concentrated feeds, as a component of the technologies for obtaining them, constitutes one of the basic operations, while at the same time being a large consumer of energy.

The comminution (size reduction) of concentrated feeds, depending on the principles of size reduction, can be carried out using:

- stone mills in the case of dry seeds,
- roller mills with rifled rollers for dry or wet cereal seeds (when obtaining cereal flakes is desired),
- star or disc crushers for oilseeds and briquettes,
- finger crushers for processing corn cobs,
- hammer mills for all cases.

Hammer mills are the most widely used in the grinding process on livestock farms.

The working process of the mill must be regarded as a stochastic process described by pseudo-static methods *(Institut National de la Recherche Agronomique, 1994)*. In this case, the established operating regime of the mill is a continuous, random, stationary process.

As a result of the size reduction process, a multitude of small particles are formed, so comminution can be characterized as a process of producing new surfaces of the material particles. The size of the entire mass of pulverized material, as a static mass, is assessed by its content of certain size classes (fractions), i.e., by its particle size composition or granulation. Almost all crushing and grinding of inorganic materials involves reducing from one size distribution to a smaller one.

For this reason, many fragmentation theories are based on the dimensional connection from one distribution to another.

The size reduction process in hammer mills is influenced by the following factors: technological, mechanical, design-related, and functional.

The main **mechanical factors** influencing the comminution process in hammer mills are:

- the impacts applied by the hammers to the feed particles,
- the loss of deformation energy during the impact,
- the peripheral speed of the hammers,
- the speed of movement of the feed layer in the grinding chamber,
- the fan effect produced by the hammer rotor,
- the moment of inertia of the hammer rotor *(Oprescu et al., 2023)*.

The **design factors** influencing the comminution process are:

- the size of the grinding chamber,
- the structural shape of the hammers,
- the clearance between hammers and screen,
- the structural shape of the rifling,
- the method of feeding the equipment with feed,
- the mode of discharging the ground product.

The comminution of seeds in hammer mills can be considered as consisting of three phases:

1. The size reduction of feed particles due to the impact with the rotating rotor hammers upon entering the grinding chamber;
2. The size reduction of particles in non-uniform motion resulting from the first impact and projected by the hammers onto the rifled counterstrike plates and also onto the edges of the screen openings bordering the grinding chamber;

3. The size reduction of feed particles as a result of mutual collisions within the grinding chamber.

MATERIALS AND METHODS

Hammer mills, whether with a closed or an open chamber, are currently the most widespread and widely used machines for preparing concentrated feeds on livestock farms, while also being the largest energy consumers. INMA Bucharest has over time undertaken a series of projects for hammer mills.

Closed-chamber hammer mills (Figure 3, a and b) are those mills where the feeding is done frontally (axially or off-center), the lateral surface being completely enclosed by the sieve and counterstrike plates or only by the sieve. The hammer mill MC 22, Figure 3, designed by INMA Bucharest, is a closed-chamber mill.

The hammer rotor is fixed in the mill housing directly onto the electric motor shaft by a key and safety screw. The rotor consists of a disc made of steel sheet welded to a hub. On the front side of the disc, 24 hammers are mounted crosswise on four pins. On each pin, six hammers are mounted, spaced by distance bushings.

The hammers are arranged on the pins so as to ensure the largest possible contact surface with the ground product. The hammers can be mounted in four positions; they should only be replaced after complete wear. If the pins on which the hammers are mounted become worn, the hammers can be moved to the other four unused pins. Replacing the hammers on worn pins must be done for all four rows of hammers while keeping the initial mounting order (hammer, spacer, hammer, etc.).

Basically, the dynamics of the hammer mill (Figure 3) can be imagined as a physical model composed of three elements:

1. The rotor as a generator of impact pulses, producing a large number of shredded particles;
2. A layer of product-air as a volume (or mass) that maintains the balance between two simultaneous continuous processes: “multiplication” or “augmentation” (hammer rotor’s capacity) and “death” (the sieve’s capacity);
3. The perforated surface of the grinding chamber (the sieve as a screen), which limits the intensity of the material stream passing through the mill.

The mill’s working process should be regarded as a stochastic process described by pseudo-static methods. In this case, the established operation of the mill is a continuous, incidental, stationary process.

Grinding in the hammer mill is influenced by technological, mechanical, constructive, and functional factors.

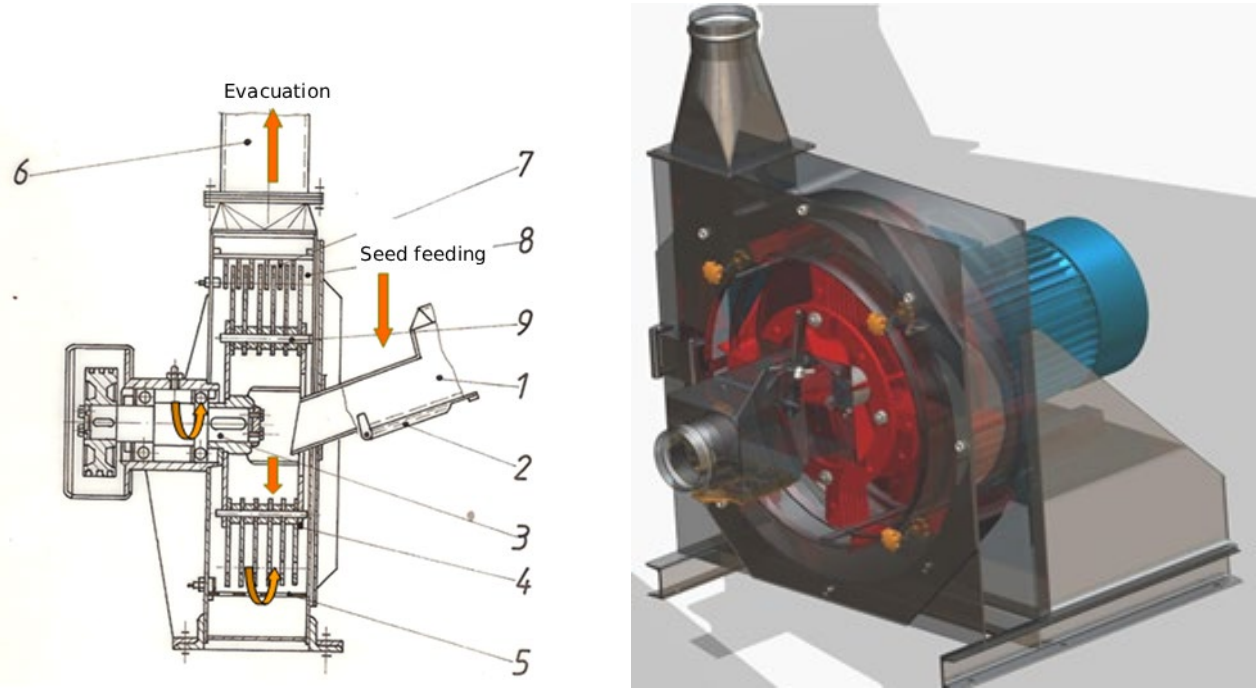
The main mechanical factors that influence grinding in hammer mills are:

- the impacts applied by the hammers to the feed particles,
- the loss of deformation energy during the impact,
- the peripheral speed of the hammers,
- the speed of movement of the feed layer in the grinding chamber,
- the fan effect produced by the rotor with hammers,
- the moment of inertia of the rotor with hammers.

The constructive factors influencing the grinding process are:

- the size of the grinding chamber,
- the constructive shape of the hammers,
- the size of the gap between hammers and sieve,
- the constructive shape of the grooves,
- the method of feed supply to the equipment,
- the discharge of the ground product.

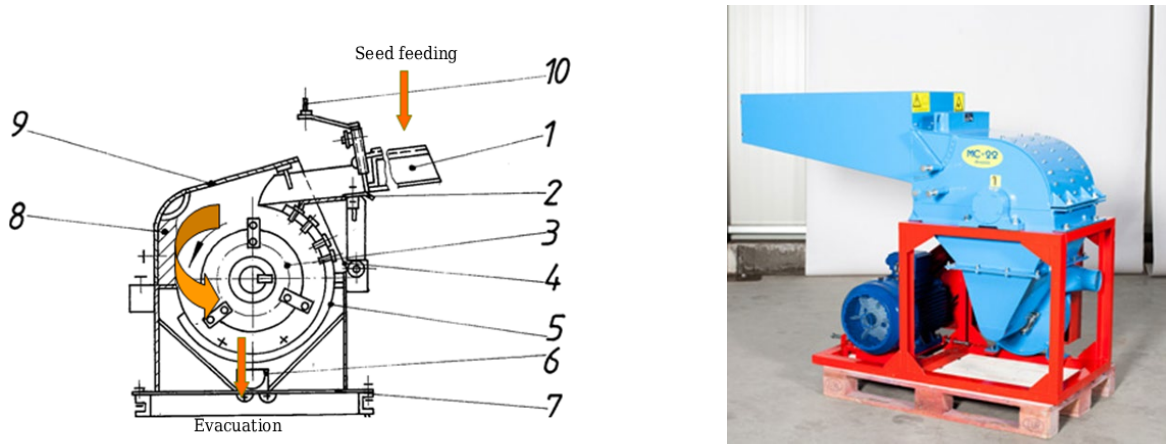
The open-chamber hammer mill (Figure 4) *(Karimirad et al., 2020).* is a mill where feeding is done radially, tangentially, or radially-tangentially. Thus, feed enters through an opening at the periphery. Feeding is done tangentially by free flow along the entire length of the grinding chamber.



a b

Fig. 3 - Closed chamber hammer mill

a- 1- feed chute; 2- magnet box; 3-shaft; 4-rotor with hammers; 5-screen; 6-grinding discharge pipe; 7-counter-beater with plates;8- hammers; 9- bolt.
b- The hammer mill HM 22
(Păun et. al., 2018)



a b

Fig. 4 - Open chamber hammer mill

a- geometric model, 1- feed chute; 2-magnet box; 3-hammer rotor; 4- ribbed plates;5- sieve; 6-transport pipeline; 7- framework; b- MC 22 open chamber mill
(Păun et. al., 2018)

When entering the grinding chamber, cereal seeds are subjected to strong blows from the hammers. Due to these blows, the cereal seeds are crushed, and the resulting particles are projected onto the rifled plates (counter-knives), where a second comminution occurs.

From these plates, the resulting particles ricochet and return to the hammer zone, after which the phenomena repeat.

The comminution phenomenon also continues in the area of the sieve due to the shocks and friction between the feed particles and the edges of the sieve openings.

The sieve mainly acts as a separation (discharge) system for the ground product.

Particles smaller than the sieve openings, under the action of the airflow created by a fan (mounted outside the mill) and centrifugal forces, pass through the sieve and reach the discharge and transport pipe, which connects to the separation and collection systems.

In these mills, the comminution of feed is achieved mainly due to the collisions between the hammers and the feed particles, as well as the counterstrike plates.

The counterstrike plate is the fixed component in the grinding chamber that participates in the seed comminution operation and can have various shapes: cylindrical, semi-cylindrical, or a cylindrical-sector shape with an active surface that is rifled, toothed, or perforated.

There are situations when the counterstrike plate is absent, and its role is taken over by the perforated sieve. Using a counterstrike plate with rifling or teeth leads to the best results in terms of comminution quality.

The peripheral speed of the hammers is the most important factor because it influences the impact velocity and the flow of the material layer in the grinding chamber. Feed particle comminution occurs at a peripheral speed of the hammers greater than the destruction speed of the material. The destruction speed, under the conditions of seed comminution by impact, is given by the relationship *(Stroescu et. al., 2021a):*

$$v_{dsl} = \sigma_{ds}\sqrt{\frac{E}{\rho}E} \tag{1}$$

where: ρ - density, kg/m^3;

$$\sqrt{\frac{E}{\rho}} = c_0$$

propagation speed of elastic waves, m/s.

By analyzing relation (1), it is found that the critical destruction speed depends on the physical-mechanical properties of the material subjected to the hammer blows.

Therefore, a correlation must be established between the hammer speed and the physical-mechanical properties of the product to be ground.

To determine the optimal hammer speed, the following relation is used (*Revenko V., 1971*):

$$v_c = v_p \frac{1}{1-k} = \alpha v_d \tag{2}$$

and

$$v_d = \frac{v\sigma_p}{E} \tag{3}$$

Where:

v_d - the destruction speed by impact, m/s;

v - the speed of deformation diffusion in the material, m/s;

σ_p - the material's breaking (destruction) stress, N/cm²;

E - the modulus of elasticity of the material, N/cm²;

v_c - the peripheral speed of the hammer, m/s;

k - coefficient accounting for the influence of the layer speed in the grinding chamber;

v_s - the speed of the layer on the working surface of the grinding chamber, m/s;

α - proportionality coefficient determined in practice.

RESULTS

The parameters influencing the performance of hammer mills are: Q – mill feed rate, kg/h; vc – peripheral speed of the hammers, m/s; D – diameter of the hammer rotor, m; vds – velocity of the seed layer in the grinding chamber, m/s; z – number of hammers; b – width of the hammer, mm; e – clearance (distance) between the tip of the hammers and the sieve, mm; d – diameter of the sieve openings in the grinding chamber, mm; β – coverage angle of the grinding chamber, degrees; l – length of the hammer, mm; qa – amount of air required to remove material from the grinding chamber, m³/min; A – total area of the sieve

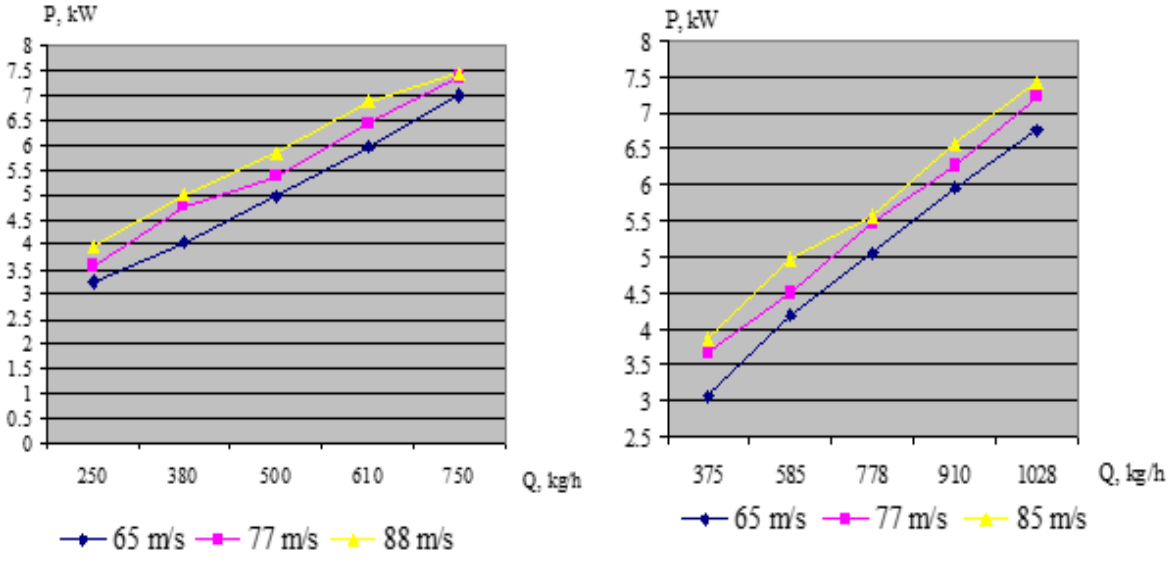
openings, mm²; M – fineness modulus of the ground material, mm; G – particle size of the ground material, mm; F – crushing strength of the seeds, kgf/cm²; E – elasticity modulus of the seeds, kgf/cm²; ρ – density of the material being ground, kg/m³; – dynamic system of rotor – hammers, counter-blade (ribbed surface).

Since not all parameters have the same influence, only a few of them were investigated experimentally. The main objective of the experimental research was to demonstrate the influence of the hammer's peripheral speed on the grinding rate Q, specific energy consumption q, and the fineness modulus M.

Determinations were carried out according to Tables 1 and 2. Based on the results obtained from the experiments, a series of diagrams were created (Figure 5).

Table 1

Nr. crt.	Processed product	The dimensions of the mill sieve holes [mm]	Peripheral speed of hammers [m/s]	Grinding rate [kg/h]	Absorbed power [kW]	Specific energy consumption [kWh/t]	Module of chopped seeds [M, mm]
0	1	2	3	4	5	6	7
1	Corn	3	65	250	3,25	13,00	0,64
2			65	380	4.04	10,60	0,63
3			65	500	4,94	9,88	0,62
4			77	250	3,55	14,2	0,62
5			77	380	4,75	12,5	0,61
6			77	500	5,35	10,24	0,60
7			85	250	3,95	15,8	0,60
8			85	380	4,99	13,1	0,59
9			85	500	5,85	11,7	0,58
10		5	65	375	3,28	8,75	0,96
11			65	585	4,25	7,26	0,97



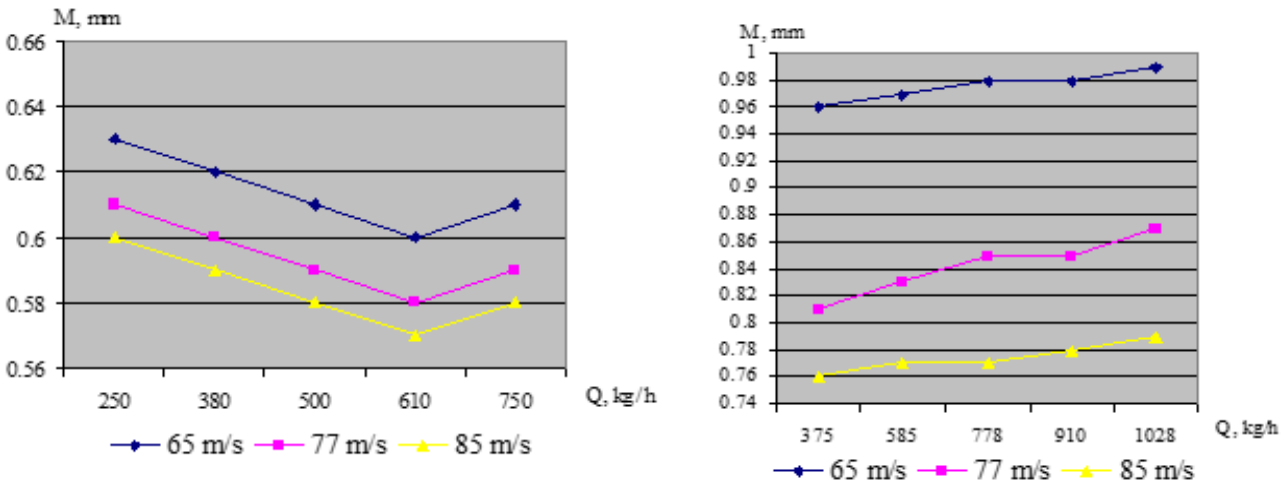


Fig. 5 - Influence of hammer speed on mill performance when grinding corn seeds
(Stroescu et. al., 2021a)

CONCLUSIONS

The integration of leguminous plants into livestock feed formulations is essential for enhancing nutritional quality and supporting sustainable animal production. Their rich protein content, essential amino acids, and vital nutrients like calcium and phosphorus significantly improve feed efficiency and animal health.

The grinding process plays a pivotal role in maximizing the bioavailability of these nutrients, ensuring optimal particle size for digestion and absorption. By leveraging advanced grinding technologies, farmers can produce high-quality concentrated feeds that meet global standards while reducing costs.

The environmental benefits of legumes, such as nitrogen fixation, further underscore their value in sustainable agriculture. This study highlights that optimizing the grinding process for leguminous plants is critical for developing effective, eco-friendly feed solutions that drive livestock productivity and farm efficiency.

In the grinding of food products any mathematical formula representing the cause and effect of particle size reduction should take into account the moisture content. The energy required for any specific size reduction situation depends, first, on the type of material to be reduced; second, on the machine or method used to achieve the reduction; and third, on the specific dimensional opening through which the material is fractured.

These three variables must be included in any mathematical expression representing comminution. The hardness of the seeds has a significant influence on the formation of intermediate products and also serves as a criterion for evaluating energy consumption during grinding.

Knowing that feed derived from cereal seeds behaves as elastic, plastic, and viscous bodies, but at the same time as complex colloidal, capillary-porous structures where each part of the seed behaves differently, determining the resistance force for grinding under different operating conditions allows for the proper establishment of the constructive and functional parameters of hammer mills.

Research has shown that, for each product subjected to grinding, achieving the required degree of fineness necessitates an optimal peripheral speed of the hammers.

Analyzing the graphs in Figure 5, obtained from grinding corn and barley seeds with sieves having openings of ø = 3 mm and ø = 5 mm, it is observed that for both products, an increase in the peripheral speed of the hammers—while the required power for operation remains within very close limits—leads to a decrease in grinding capacity, and the fineness modulus is reduced. The most favorable results are obtained at a hammer peripheral speed of 65 m/s.

ACKNOWLEDGEMENT

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DETERMINANT FACTORS FOR THE SUSTAINABILITY OF VEGETABLE CROPS – A REVIEW
/
FACTORI DETERMINANȚI AI SUSTENABILITĂȚII CULTURILOR LEGUMICOLE – REVIEW

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Keywords: *sustainable agriculture, agroecosystems, vegetable production, resilience*

ABSTRACT

Vegetable production represents one of the most intensive branches of agriculture, based on mechanization, chemical inputs, irrigation and high-performing cultivars. In the current context, the sustainability of vegetable production becomes a priority, aiming to ensure the achievement of safe and nutritious yields without compromising ecological balance and resources for future generations. The present paper is a review study, with the aim of identifying and analyzing the main determinant factors of sustainability in vegetable crops, focusing on the pedological, climatic, biological, and socio-economic dimensions. The documentation was carried out based on the specialized literature, complemented by the practical observations regarding the specific conditions of vegetable cultivation in Romania. The results highlight that the viability of sustainable vegetable production systems depends on the soil quality, climate conditions, use of adapted and resistant cultivars, as well as access to the technical and financial resources, confirming that the transition towards sustainable agricultural practices is an essential requirement for the development of this sector.

REZUMAT

Legumicultura reprezintă una dintre cele mai intensive ramuri ale agriculturii, bazată pe utilizarea mecanizării, a chimizării, a irigațiilor și a cultivarelor performante. În contextul actual, sustenabilitatea producției legumicole devine o prioritate, având rolul de a asigura obținerea unor recolte sigure și nutritive, fără a compromite echilibrul ecologic și resursele pentru generațiile viitoare. Prezenta lucrare este un studiu de tip review, având ca scop identificarea și analiza principalilor factori determinanți ai sustenabilității culturilor legumicole, cu accent pe dimensiunea pedologică, climatică, biologică și socio-economică. Documentarea s-a realizat pe baza literaturii de specialitate, completată cu observații practice privind condițiile specifice de cultivare a legumelor în România. Rezultatele obținute arată că viabilitatea sistemelor legumicole sustenabile depinde de calitatea solurilor, de regimul climatic, de utilizarea cultivarelor adaptate și rezistente, precum și de accesul la resurse tehnice și financiare, ceea ce confirmă că tranziția spre practici agricole sustenabile reprezintă o condiție esențială pentru dezvoltarea acestui sector.

INTRODUCTION

Sustainable agriculture, sometimes incorrectly referred to as durable agriculture, is a complex concept that is difficult to define uniformly, as it combines a philosophical dimension, oriented toward the responsible use of natural resources, with a practical dimension, based on the application of adapted agricultural technologies *(Velten et al., 2015; von Wirén-Lehr, 2001).* In Romanian specialist literature, the term "sustainability" is relatively recent, having been introduced around the year 2000, with multiple interpretations and no full consensus on its content *(Munteanu, 1999).*

The importance of sustainable agriculture goes beyond agricultural production, having direct implications for rural development. The viability of farms is an essential factor in maintaining the economic, social, and cultural balance of rural areas, and the adoption of sustainable practices can contribute to the revitalization of communities and increase their resilience.

Numerous authors have outlined definitions of sustainable agriculture, converging on the idea that such an agricultural system must reduce environmental degradation, be economically viable, support the stability of rural communities, and ensure consistent productivity in the short and long term. According to the definition in the Brundtland Report - Our Common Future (1987), sustainable development is characterized as "development that meets the needs of the present without compromising the ability of future generations to meet their own needs".

A reference definition is provided by the United States Congress *(U.S.C., 1990),* which describes sustainable agriculture as "an integrated system of crop and animal production practices, applied specifically to a particular location, which, in the long term, meets human needs for food and fiber, improves the quality of the environment, makes efficient use of non-renewable resources and resources available on the farm, and integrates natural biological cycles and mechanisms, maintains the economic viability of farms, and improves the quality of life for farmers and society as a whole". Munteanu (1999), describes sustainable agriculture as "that form of agriculture which can evolve indefinitely towards ever greater usefulness to humans, towards increased efficiency in the use of resources, and in balance with the environment, favorable to both humanity and most species" (Fig. 1).

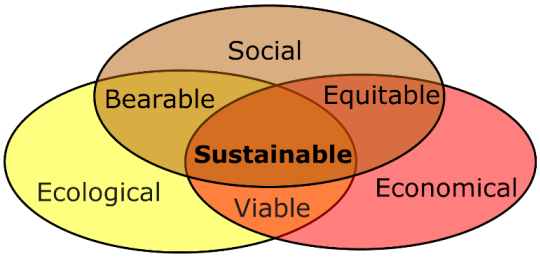

Fig. 1 - Diagram defining sustainability

From an applied perspective, sustainable agriculture can be viewed as a compromise between intensive agriculture and alternative systems (ecological, organic, biodynamic), seeking to integrate the advantages of both types *(Reganold and Wachter, 2016).* The goal is to reduce the negative effects of excessive chemical use specific to conventional agriculture and, at the same time, avoid the productivity limitations characteristic of alternative systems *(Ponisio et al., 2015; Teliban, 2011).* Thus, sustainable agriculture proposes a balance between achieving competitive yields and protecting the environment and consumer health, under conditions of economic efficiency *(Pretty et al., 2018; Tittonell, 2014).*

This vision implies a cooperative relationship between humans and nature, based on learning and respecting natural mechanisms, and also has an ethical dimension, through the responsibility to pass on viable and productive production systems to future generations.

In vegetable farming, the application of sustainability principles is particularly relevant due to the diversity of cultivated species, the intensity of inputs used, and the variability of cultivated areas - from small family farms to large commercial farms *(Stoleru, 2013).* The integration of good agricultural practices that are efficient and adaptable in the long term can transform vegetable growing into a concrete example of the implementation of sustainable agriculture in Romania (Fig. 2).

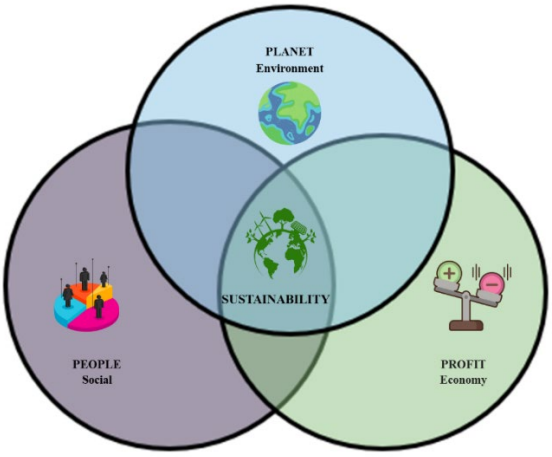

Fig. 2 - A model for achieving sustainability

In this context, the purpose of this paper is to analyze and highlight the main determinants of vegetable crop sustainability, providing scientific and practical guidelines for the transition to sustainable production systems.

MATERIALS AND METHODS

This paper is a review study that aims to identify and analyze the factors that determine the sustainability of vegetable crops *(Moher et al., 2009).* The documentation was based on consulting a wide range of scientific sources - articles published in internationally indexed journals, specialized works, monographs, and technical reports - selected mainly from the Web of Science, Scopus, Google Scholar, and CAB Abstracts databases *(Snyder, 2019).*

The bibliographic search was conducted using combinations of keywords such as “sustainability in vegetable production”, “determinant factors”, “soil quality and vegetables”, “climate change and vegetable crops”, “socio-economic aspects of sustainable horticulture”, to which terms such as “resilience in horticultural systems”, “integrated pest management in horticulture”, and “sustainable practices in vegetable farming” to best cover the pedological, climatic, biological, and socio-economic dimensions of sustainability. For relevance, priority was given to articles published in the last 25 years (2000–2025), supplemented by older fundamental sources of reference value for the field.

The inclusion criteria focused on works that explicitly address the pedological, climatic, biological, and socio-economic dimensions of sustainability in vegetable farming, with an emphasis on production systems in Europe and Romania, but also on comparative examples at the international level *(Paré et al., 2015).*

The analysis aimed to highlight the most important factors influencing the sustainability of vegetable crops, as well as to identify good practices and recommended research directions in the literature.

RESULTS

I. PEDOLOGICAL FACTORS

Soil is the fundamental element of any sustainable agricultural system, serving not only as a physical support for plants, but also as a "living organism" that contributes to maintaining the fertility, biodiversity, and stability of agroecosystems *(Davidescu and Davidescu, 1992; Lal, 2015).* In vegetable farming, soil quality plays a decisive role in achieving stable and competitive yields, and long-term sustainability depends on farmers' ability to conserve and improve its physical, chemical, and biological properties.

Fundamental indicators for evaluating soils intended for vegetable cultivation include texture, organic matter and humus content, C/N ratio, soil reaction, degree of salinization, and level of essential nutrient supply *(Brady & Weil, 2017).*

Soil texture and structure

Medium soils with loamy, loamy-clay, or loamy-sandy textures are considered the most favorable because they provide an optimal balance between water retention capacity, aeration, and suitability for agricultural work *(Brady and Weil, 2016; Stoian, 2005; Munteanu et al., 2008)*. From a sustainability perspective, these soils require careful management to prevent compaction or loss of fertility through intensive exploitation *(Lal, 2020).*

Organic matter and humus

Organic matter (OM) content is essential for maintaining soil fertility and structure, being directly correlated with the productivity and stability of vegetable systems. Levels of 60–80 g OM/kg in loamy soils and 40–60 g/kg in sandy soils are considered optimal (*Stoian, 2005).* Humus, the main component of the clay-humic complex, ensures cation exchange capacity, organic nitrogen storage, and nutrient retention. Critical thresholds are a minimum of 2% humus for field crops and 6% for vegetables *(Munteanu et al., 2008).* Below these values, the sustainability of vegetable systems is compromised because yields become unstable and the soil reduces its ability to recover and maintain long-term fertility *(Lal, 2015; Lehmann and Kleber, 2015).*

C/N ratio and nutrient balance

The C/N ratio influences the rate of organic matter mineralization and nitrogen availability to plants *(Xu et al., 2013).* A balanced ratio supports decomposition processes and prevents nutrient imbalances **(Chen et al., 2018)**. From a practical perspective, monitoring the C/N ratio is crucial on farms that rely on organic fertilization, as it ensures a gradual and sustainable release of nutrients *(Geisseler and Scow, 2014).*

Soil reaction

Soil reaction, expressed by soil pH, directly influences nutrient availability *(Brady and Weil, 2017).* Most vegetable species prefer a neutral or slightly acidic pH (6.5–7.0), but some can tolerate slightly alkaline values of up to 7.5. Below pH 5, phosphorus becomes inaccessible, and above 8.5, the absorption of microelements (Zn, B, Mn, Cu) is limited, affecting the quality and quantity of production *(Volf, 2008).* In sustainable systems, maintaining an optimal pH through amendments and crop rotation ensures long-term balance, reducing dependence on chemical fertilizers *(Sposito, 2016).*

Soil salinity

Salinity is a limiting factor with a major impact on the sustainability of vegetable crops. Species tolerance to salinity varies considerably, and sensitivity to salt accumulation can lead to significant losses even under moderate salinization conditions *(Davidescu & Davidescu, 1992; Machado & Serralheiro, 2017).* In protected crops (greenhouses, solariums), where irrigation and fertilization are intense, the risk of salt accumulation is increased, making it necessary to periodically monitor irrigation water and soil to prevent its degradation *(Shrivastava & Kumar, 2015).*

Macronutrients and soil fertility

The level of macronutrient supply (N, P, K) completes the picture of fertility *(Fageria, 2009).* In sustainable agriculture, nitrogen must come mainly from organic sources, released gradually through the mineralization of organic matter. Phosphorus and potassium are also essential for stable yields, as their deficiency causes annual fluctuations and a decline in product quality. Integrated fertilization practices, which combine organic and mineral inputs, are effective solutions for maintaining long-term soil sustainability *(Bindraban et al., 2015; Roy et al., 2006).*

Implications for sustainability

Soil factors directly determine the viability of vegetable crops *(Lal, 2015).* Effective management of organic matter, maintaining adequate humus content, monitoring pH and salinity, and ensuring nutritional balance are essential conditions for a sustainable system *(Montanarella and Panagos, 2021).* In the context of climate change and intensified agricultural practices, protecting soil resources is becoming a strategic priority, without which the resilience and competitiveness of vegetable production cannot be guaranteed *(FAO & ITPS, 2015)*.

II. CLIMATIC FACTORS

Climate is one of the key factors determining the sustainability of vegetable crops, through its direct influence on plant growth, development, and productivity *(IPCC, 2023).* Climate variability and the increasing frequency of extreme events affect not only production levels but also the economic viability of farms *(Wheeler and von Braun, 2013),* putting pressure on farmers to adapt their technologies and crop assortment *(Lesk et al., 2016).*

Light and solar radiation

Light is the main source of energy for photosynthesis and, implicitly, for stable and high-quality production *(Taiz et al., 2015).* The intensity, duration, and quality of solar radiation influence physiological processes (photosynthesis, respiration, transpiration, flower bud differentiation) and determine crop productivity *(Hogewoning et al., 2010; Marcelis et al., 2006).*

From a sustainability perspective, light management poses two practical challenges: protecting crops during summers with excessive insolation and ensuring sufficient lighting in winter. Modern solutions - shading and ventilating protected spaces in summer and supplementing with artificial light in winter - allow farmers to reduce losses and maintain consistent production *(Gómez and Mitchell, 2015; Olle and Viršile, 2013).*

Heat and temperature regime

Temperature determines the zoning of vegetable crops and the length of the growing season. Each species has optimal, minimum, and maximum temperature thresholds, and exceeding these thresholds affects both the quantity and quality of production *(Hatfield and Prueger, 2015).*

Late spring frosts, winter frosts, and summer heat waves are major limiting factors (*Lesk et al., 2016).* From a sustainability perspective, these risks require the use of cultivation methods adapted to local conditions, the adjustment of the crop calendar, and the implementation of technologies to protect against frost and heat (tunnels, shading, anti-frost screens, mulching) *(Wheeler and von Braun, 2013).* Thus, thermal regime management becomes a practical condition for maintaining production stability in the context of climate change *(IPCC, 2023).*

Water and humidity regime

Water is one of the main limiting factors for the sustainability of vegetable crops *(FAO, 2017).* Most vegetable species have high requirements for soil and air humidity, and variations - whether deficit or excess - have negative effects on yield and quality *(Fereres and Soriano, 2007; Geerts and Raes, 2009).*

From a practical point of view, a sustainable system involves the adoption of drip irrigation, monitoring of soil and air humidity, drainage in areas with excess moisture, and the application of mulch to conserve moisture. These technologies optimize resource consumption and reduce environmental impact, contributing to the resilience of vegetable systems *(Lamont, 2016).*

Air and its composition

The composition of air influences plant metabolic processes. Oxygen is necessary for root respiration, and CO_2 concentration determines photosynthesis. In protected spaces, artificial CO_2 supplementation can increase tomato, cucumber, and lettuce yields by 30–50% *(Ainsworth and Long, 2005).* At the same time, atmospheric pollution affects plant health and reduces product quality *(Feng et al., 2015*). From a sustainability perspective, managing air quality in greenhouses and solariums, as well as avoiding planting crops in polluted areas, are essential measures for protecting production.

Moderate winds can have positive effects by drying leaves and reducing the risk of cryptogamic diseases, but strong winds cause mechanical damage, increase evapotranspiration, and intensify soil water evaporation. The use of forest curtains or artificial barriers is a practical measure that directly contributes to the sustainability of vegetable systems, protecting crops and reducing economic losses *(Brandle et al., 2004; Heisler and DeWalle, 1988).*

Implications for sustainability

Analysis of climatic factors shows that they can be both an optimization resource and a limiting factor. In the context of climate change, marked by prolonged droughts, heat waves, and extreme events, the sustainability of vegetable crops depends on farmers' ability to integrate modern microclimate control technologies, adopt resistant cultivars, and apply practices that reduce vulnerability *(IPCC, 2023; Lesk et al., 2016; Wheeler and von Braun, 2013)*. Intelligent management of light, temperature, humidity, and wind transforms the climate, often perceived as a constraint, into a partially controllable factor capable of supporting the viability and competitiveness of vegetable production *(Hatfield and Prueger, 2015).*

III. BIOLOGICAL FACTORS

Biological factors exert a major influence on the sustainability of vegetable crops, as they directly influence production levels and stability, as well as the degree of dependence on external inputs *(Altieri et al., 2015; Munteanu et al., 2012)*. These include the species and cultivars used, as well as the pressure exerted by weeds *(Gaba et al., 2016),* diseases, and pests *(Lamichhane et al., 2016).* How these factors are managed defines the long-term viability of vegetable agroecosystems.

Cultivar and biodiversity

The wide diversity of vegetable species and cultivars is an important resource for sustainable agriculture *(Khoury et al., 2014).* Choosing the right cultivar has a direct impact on productivity and production quality, but also on input requirements. Cultivars that are resistant or tolerant to diseases and pests reduce the need for chemical treatments, lowering costs and negative environmental impacts *(Dwivedi et al., 2016)*. In addition, the use of greater genetic diversity (local varieties and populations, adapted hybrids, crop association or rotation with different species) increases the ability to adapt to variable climatic conditions and biotic stresses *(Hajjar et al., 2008).* Thus, genetic biodiversity becomes a pillar of sustainability by reducing vulnerability and increasing the resilience of vegetable systems *(Ambăruș, 2009; Munteanu, 2000).*

Weeds

Weeds compete with crops for resources and can promote the establishment of pathogens and pests *(Oerke, 2006).* In a sustainable approach, the goal is not complete eradication, but keeping them below the economic damage threshold through integrated management *(Swanton & Weise, 1991).* Crop rotation, associating vegetable crops with repellent species, organic mulching, preventive mechanical work, or maintaining habitats for beneficial entomofauna are methods that reduce weed pressure without compromising the balance of the agroecosystem *(Bàrberi, 2002; Nichols et al., 2015).* These practices contribute to biodiversity conservation and reduce herbicide use, making vegetable systems more environmentally friendly and more acceptable to consumers *(Harker and O'Donovan, 2013).*

Pathogens

Diseases caused by viruses, bacteria, and fungi are major disruptive factors in vegetable agroecosystems *(Călin, 2005; Strange and Scott, 2005).* In conventional agriculture, these problems are managed through frequent chemical treatments, but in a sustainable system, the emphasis is on disease prevention through the use of healthy seeds, crop rotation, compliance with phytosanitary hygiene, and the cultivation of resistant varieties *(Lamichhane et al., 2016).* Biological treatments and the use of natural extracts complement these measures, reducing environmental impact and enhancing food safety *(Nega, 2014).*

Pests

Pests cause considerable damage to vegetable crops. Some invasive species, such as *Tuta absoluta* and *Helicoverpa armigera*, have proven to be extremely aggressive, especially in greenhouse tomato crops *(Desneux et al., 2010; Burgio et al., 2020).* In conventional agriculture, pest control is based on repeated chemical treatments, but in sustainable systems the emphasis is on integrated measures: continuous crop monitoring, the use of pheromone traps, and the introduction of biological control agents *(Biondi et al., 2018; van Lenteren et al., 2018)*. The "dirty field" method is also used, whereby small populations of pests are tolerated without immediate treatment. This allows them to be kept below the economic damage threshold and reduces pressure on the environment *(Călin, 2005)*. This reduces costs and ecological impact while maintaining productivity.

Implications for sustainability

Biological factors are closely interlinked, and their interactions have cumulative effects on crops. Managing them in sustainable systems cannot be unilateral, but requires an integrated approach, tailored to each agroecosystem, so as to limit the risk of economic losses and respond to consumer demand for safe and healthy products *(Barzman et al., 2015).* At the same time, the conservation of crop biodiversity and the application of integrated plant protection techniques contribute to the long-term resilience of *farms (Hajjar et al., 2008)*. Thus, biological factors, often perceived as limiting, become elements that, through proper management, can support the development of competitive and environmentally friendly vegetable systems *(Pretty et al., 2018).*

IV. TECHNICAL AND SOCIO-ECONOMIC FACTORS

The sustainability of vegetable crops is decisively influenced by technical and socio-economic factors *(Tittonell, 2014).* These factors include the level of mechanization and agricultural infrastructure, access to financial resources and support funds, the quality of the workforce, the organization of markets, and the legislative and institutional framework *(FAO, 2014; Gadanakis et al., 2015).* They determine not only the immediate efficiency of production, but also the ability of farms to remain viable in the long term in a constantly changing economic and climatic environment (*Darnhofer et al., 2011).*

Mechanization and modern technologies

Vegetable growing is one of the most intensive branches of agriculture, requiring a high volume of investment and inputs per unit of area. The mechanization of work - from land preparation to harvesting - leads to high energy consumption and can have negative effects on soil structure and fertility if not properly managed *(Lal, 2015).* In sustainable systems, the goal is to reduce unnecessary passes, use conservative techniques (minimal tillage, mulching, rotation), and integrate efficient irrigation systems *(Pereira et al., 2012; Kassam et al., 2015)*. By adopting these solutions, a more rational use of resources is achieved and the ecological footprint of vegetable farms is reduced.

Financial resources

A sustainable vegetable production system requires constant investment in infrastructure (irrigation, protected areas, storage, modern equipment). Limited access to financial resources and European funds remains one of the biggest barriers to sustainability *(Gadanakis et al., 2015).* Ad hoc financial support, such as the "Tomata" program *(https://legislatie.just.ro/public/DetaliiDocument/296454),* plays a temporary stabilizing role but does not solve structural problems. In the long term, sustainability depends on coherent policies that facilitate the conversion to environmentally friendly technologies and provide farmers with the tools to adapt to climate change *(FAO, 2014).*

Labor force and vocational training

Vegetable growing involves a large amount of manual labor, especially during the maintenance and harvesting stages. The availability and quality of the labor force directly influence the productivity and competitiveness of farms. In rural areas, labour migration to other sectors or abroad makes it difficult to meet staffing needs, which increases the pressure for mechanisation and limits the capacity for farm expansion

(Kasimis, 2008; Martin, 2016). At the same time, the level of professional training of farmers directly influences the adoption of sustainable practices *(Knierim and Proctor, 2013).* Professional training for vegetable growers and access to modern information are essential conditions for the adoption of sustainable agricultural practices *(FAO, 2017).*

The market and consumers

Another condition for the sustainability of vegetable farming systems is the existence of stable and predictable markets. Price fluctuations, competition from imported products, and the lack of well-organized distribution channels reduce the competitiveness of local *producers (Brunori et al., 2016; Ilbery and Maye, 2005)*. On the other hand, growing consumer interest in healthy, low-input products represents a major opportunity for sustainable vegetable farming *(Grunert, 2011; Teliban, 2011).*

Agricultural policies and institutional framework

Romania's integration into the European Union has led to alignment with European standards on production and environmental protection (European Commission(a)). However, for vegetable farming to become sustainable, agricultural policies need to be better adapted to national realities. Support through subsidies for ecological inputs, investments in irrigation infrastructure, and facilitating access to markets are essential measures (European Commission (b); FAO, 2017). Without them, farmers remain vulnerable to climatic and economic volatility, and long-term sustainability is difficult to ensure.

Implications for sustainability

Technical and socio-economic factors define the framework within which agronomic decisions become viable or, conversely, impossible to implement. Without access to modern technologies, financial resources, skilled labor, and competitive markets, even the most favorable soil and climate conditions cannot ensure sustainability *(Darnhofer et al., 2011; Gadanakis et al., 2015).* Therefore, an integrated strategy combining technical investments with tailored agricultural and social policies can transform vegetable growing into a resilient sector capable of responding to both climatic and economic challenges *(FAO, 2014).*

V. Interaction of factors and perspectives for sustainable practices

Analysis of soil, climate, biological, and socioeconomic factors highlights the fact that the sustainability of vegetable crops does not depend on the isolated action of each component, but on the interaction between them. The balance of vegetable agroecosystems is the result of complex dynamics, in which a change in one factor triggers chain reactions in the others.

Thus, soil quality can amplify or reduce the impact of climatic factors. Fertile soils with adequate organic matter content and balanced pH buffer the effects of water deficit or excess, while degraded or salinized soils increase crop vulnerability to water and heat stress *(Lal, 2015).* At the same time, climate change influences nutrient availability and organic matter dynamics, which emphasizes the need for soil conservation practices *(Altieri et al., 2015; Darnhofer et al., 2016).*

Biological factors are, in turn, closely linked to soil and climate conditions. The pressure of pathogens and pests increases under conditions of monoculture, excessive humidity, or high temperatures *(McDonald & Stukenbrock, 2016)*, making it essential to integrate crop rotation, use resistant cultivars, and apply integrated protection methods *(Barzman et al., 2015).* In the absence of these measures, the vulnerability of farms increases and dependence on chemical treatments compromises long-term sustainability.

Technical and socio-economic factors determine farmers' ability to implement these practices. Access to financial resources, irrigation infrastructure, the degree of mechanization, and the level of professional training determine the ability of farms to adopt modern solutions, such as drip irrigation, soil and microclimate monitoring, or supplementing fertilization with organic matter and materials *(Gadanakis et al., 2015; Klerkx and Proctor, 2013)*. At the same time, market stability and agricultural policies directly influence farmers' decisions to invest in sustainable technologies *(European Commission(a)).*

In perspective, maintaining the sustainability of vegetable crops requires an integrated approach that combines soil conservation practices with adaptation to climate variability, capitalizes on biological diversity, and is supported by coherent agricultural policies and socio-economic investments. Only through this holistic vision can the resilience of vegetable farms and the competitiveness of the sector be ensured in the context of climate change and market pressures.

CONCLUSIONS

Analysis of the determining factors highlights that the sustainability of vegetable crops is the result of a complex interaction between soil resources, climatic conditions, biological factors, and the technical and socio-economic context.

Soil factors define the soil's capacity to support sustainable production. Without soil conservation and improvement measures, vegetable systems become vulnerable and difficult to maintain in the long term.

Climatic factors determine crop limits and directly influence the quality and quantity of production. Adapting the crop calendar, using efficient irrigation, and protecting against extreme events are essential conditions for resilience.

Biological factors determine the degree of dependence on chemical inputs. Integrated protection practices and the maintenance of genetic diversity ensure risk reduction and strengthen production stability.

Technical and socio-economic factors have a decisive influence on farmers' ability to adopt sustainable practices. Access to financial resources, modern infrastructure, skilled labor, and stable markets are prerequisites for the implementation of environmentally friendly technologies and the strengthening of farm resilience.

The sustainability of vegetable crops depends on an integrated approach, in which each category of factors is managed in a complementary manner, and agricultural policies, research, and technology transfer play a decisive role in strengthening this process. In practical terms, this involves soil conservation, adaptation to climate variability, the use of resistant crops, the application of efficient technologies, and support for farmers through coherent agricultural policies - strategic directions through which vegetable farming can become competitive, resilient, and aligned with the principles of sustainability.

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THEORETICAL AND APPLICATIVE CONSIDERATIONS ON HYDROPONIC PLANT GROWTH
/
CONSIDERAȚII TEORETICE ȘI APLICATIVE PRIVIND CREȘTEREA HIDROPONICĂ A PLANTELOR

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ABSTRACT

Modern agriculture is undergoing a profound transformation driven by the increasing food demand and the need to reduce environmental impact. In this context, hydroponic cultivation – growing plants without soil – has become a viable and sustainable solution for achieving high-quality yields under controlled conditions. Hydroponics enables precise control of growth factors, efficient use of water and nutrients, and year-round production. This paper presents theoretical considerations regarding the principles of hydroponic systems, their classification, advantages and challenges, as well as applied aspects related to technical parameters, automation control, and development perspectives in sustainable agriculture.

REZUMAT

Agricultura modernă se află într-un proces de transformare profundă, generat de creșterea cererii alimentare și de necesitatea reducerii impactului asupra mediului. În acest context, cultura hidroponică – creșterea plantelor fără utilizarea solului – devine o soluție viabilă și sustenabilă pentru obținerea de producții de calitate în medii controlate. Hidroponia permite controlul exact al factorilor de creștere, utilizarea eficientă a apei și nutrienților, precum și producția pe tot parcursul anului. Lucrarea prezintă considerații teoretice privind principiile de funcționare, tipurile de sisteme hidroponice, avantajele și provocările acestei tehnologii, precum și aspecte aplicative referitoare la parametrii tehnici, controlul automatizat și perspectivele de dezvoltare în agricultură sustenabilă.

INTRODUCTION

Hydroponics is a set of technologies for growing plants in the absence of soil, through the controlled administration of a nutrient solution, the optimization of physicochemical factors and the integration of technological control systems. This paper summarizes the physiological foundations, the typologies of hydroponic systems (NFT, DWC, aeroponics, cultures in inert substrate, etc.), the critical parameters (pH, electrical conductivity — EC, dissolved oxygen, temperature), through comparisons with conventional agriculture regarding yield, water use and energy consumption. It also discusses economic aspects, environmental implications, current challenges (initial costs, pathogen management) and research directions, including the integration of IoT/automation, organic nutrients and hybrid systems in CEA - Controlled Environment Agriculture, *(Ganapathy R. et al., 2023).*

Demographic pressures, climate change and resource limitations (agricultural land and drinking water) are driving an intense search for efficient and resilient agricultural technologies. Hydroponics, as part of CEA, offers the possibility of producing high-density food on small areas, through fine environmental control and substantial water savings, *(Garzón, J., et al., 2023).* Recent literature shows that CEA and

hydroponics can increase productivity per unit area and reduce production variability caused by climatic factors, making them attractive options for urban agriculture and local food systems, *(Liping W. et al., 2025).*

In Romania, the practice of soilless farming has gained ground in recent years, representing an increasingly interesting alternative for agricultural producers eager to optimize cultivation processes and obtain higher yields.

The most common method is hydroponics, which involves growing plants in a controlled environment, in which their roots are suspended in nutrient solutions rich in essential minerals. This system allows for precise management of nutrients and other environmental factors, such as light, temperature and humidity, ensuring ideal conditions for plant development. In addition, soilless farming is also practiced in aeroponic systems, in which plant roots are exposed to air and nutrients are supplied in the form of a spray.

In Romania, these techniques are used mainly for growing vegetables and aromatic plants in greenhouses and protected spaces, where climatic conditions can be precisely controlled and production can be maximized on small areas. Benefiting from the support of the authorities and agricultural research, soilless farming is starting to make its presence felt more and more in the Romanian agricultural landscape, contributing to the diversification and efficiency of the agricultural sector in our country.

Plants suitable for soilless farming include: Vegetables: tomatoes, cucumbers, peppers, lettuce, spinach, cabbage, broccoli; Herbs: basil, thyme, oregano, mint, parsley, rosemary; Fruits: strawberries, berries (raspberries, blueberries), melons; Edible flowers: pansies, calendula, mustard flowers. These plants are adapted to grow in controlled environments and receive the necessary nutrients directly through the nutrient solution, without the need for traditional soil. *(FAO, 2023).*

Hydroponics changes the mechanics of nutrient uptake — instead of complex soil-plant interactions, nutrients are available directly in the hydroponic solution. The main physiological processes affected include: Ionic absorption and ionic balance: The ratio of macronutrients (N, P, K, Ca, Mg, S) to micronutrients (Fe, Mn, Zn, Cu, B, Mo, Cl) influences competition for uptake and availability at the root level. Influence of pH: The pH of the solution controls the solubility and availability of elements; the optimal range used by most horticultural crops is around 5.5–6.5. pH management is more critical in hydroponics than in soil, due to the lack of buffering. Electrical conductivity (EC): EC reflects the total concentration of salts; optimal levels vary by species and stage of development (e.g. young leaves vs. fruit). Monitoring and adjusting EC prevents deficiencies or toxicities, *(Tupili S.et al., 2024, Bruce D, Hardeep S. (2017)*.

Dissolved oxygen (DO): Roots need O_2; technologies that increase oxygenation (bubbles, aerators, aeration recirculation systems) improve root health and nutrient uptake. Water–nutrient–temperature interactions: Solution temperature affects nutrient solubility and root respiration; cold solutions can reduce uptake, too warm solutions decrease DO. These processes explain the need for continuous monitoring and dynamic management of nutrient solutions in hydroponic systems, to maintain nutritional homeostasis and plant health, *(Fathidarehnijeh, E., Hosseini, S. A., & Shahrajabian, M. H. 2023, Garzón, J., et al., 2023)*.

MATERIAL AND METHOD

Composition and Management of Nutrient Solutions. Composition of Formulations. Commercial hydroponic formulations are based on soluble salts that provide macro- and micronutrients. Commercial models start from stoichiometric principles to ensure adequate N:P:K ratios and Ca:Mg balance. In practice, solutions are adjusted according to species and stage (germination, vegetative, flowering, fruiting), *(Harper Adams University / DEFRA. 2023).*

Operational Parameters.pH: Maintain between 5.5–6.5 (variable depending on species) prevents precipitation or lack of trace elements. Automatic monitoring reduces variations. EC: for lettuce EC 1.2–1.8 dS/m; for tomatoes and fruit crops EC can vary 2.0–3.5 dS/m during the productive phase. Adjustments should be made gradually. Hydro How-To Solution renewal: Frequency varies (partial vs. total); a common management is partial renewal to control element accumulation or imbalances, *(Bruce D. et al., 2017).*

Various ways of implementing the concept of hydroponics have been materialized, technically called hydroponic systems. From the point of view of the location of the nutrient solution, hydroponic systems are divided into two main categories: • SHP (passive hydroponic systems, the nutrient solution has a static location in a container, without changing position). From the storage container, the nutrient solution is directed to the roots of the cultivated plants using a wick, through the phenomenon of capillarity. The growth medium must have good water, nutrient and air retention properties, being interposed between the plant roots and the nutrient solution, *(Jones, J. B. Jr. 2004).*

SHA (active hydroponic systems). These hydroponic culture methods require, in one way or another, the partial or total change of the location of the nutrient solution, using a recirculation pump and a conjugate aeration or oxygen injection system in the nutrient solution *(Velázquez-González, R. S., Rodríguez-Reséndiz, J., & Cruz-Hernández, C., 2022)*. Taking these considerations as a starting point, the specialized literature unanimously classifies six basic hydroponic systems, which constitute references for the practical implementation of this method of plant cultivation *(Keith, 2003):* the wick-fed hydroponic system, floating bed system, ebb and flow hydroponic system, nutrient film hydroponic system (NFT System), drip hydroponic system, aeroponic system. Remarkably, these mainstream hydroponic systems have developed hundreds of combinations and technical variations of one or more established methods *(Wilson and Brian, 2006).*

The wick-fed hydroponic system (Wick System).It is one of the simplest and most unpretentious passive hydroponic systems. The nutrient solution has a static location, in the storage tank, being taken up and led to the roots of the plants through one or more wicks, made of materials with a high capacity for absorbing nutrient solutions (for example: cylindrical or flat cotton fabric). This method is similar to the operation of old kerosene lamps, powered by a wick. The growth medium (the support in which the root system of the cultivated plant is fixed and in which it has developed), *(Ngcobo, B. L., Moyo, N., & Aluko, O. 2024)* is made of materials with good absorbing and retaining properties of the nutrient solution (mixture: perlite, vermiculite, coconut fiber, horticultural glass wool).

Nutrient solution. It is an aqueous solution (aqueous solution) of the main inorganic ions, obtained by dissolving the soluble salts of the essential elements necessary for plant growth and development. In these solutions, various chemical and physical forms of the mentioned elements can coexist (free ions, soluble complexes, chelates, ion pairs, liquid and gaseous phases, ions with different oxidation states), making up the speciation of the chemical elements in the solution. The notion of: essential element signifies that element that has a fundamental physiological role, its absence preventing the complete completion of the life cycle of the plant. There are 16 chemical elements considered essential elements (C, H, O, N, P, K, Ca, Mg, S, Fe, Cu, Mn, Mo, B, Cl, Zn). Being absorbed in larger quantities by plants, some of the essential elements constitute primary nutrients (macronutrients), of major importance being: N, P and K.

The excess or deficiency of these elements is felt and signaled promptly, through the appearance of the plant (different color and size of leaves, abnormal stem shape, delayed and reduced fruit production). Some elements in this category are absorbed in slightly smaller quantities (Ca, S, Mg) constituting the series of secondary nutrients. The main source of macronutrients (primary and secondary) is the substances used as fertilizers (chemical fertilizers), *(Rajaseger, G., Prabhu, V., & Prasad, D. 2023)*. Other chemical elements (Fe, Zn, Mn, Cu, B, Mo, Cl), called micronutrients, are absorbed in much smaller quantities, having the role of stimulating growth, compensating for toxic effects of other elements or substituting essential nutrients with a less specific role *(Prasad and Power, 1997).* In practice, the preparation procedures and recipes of nutrient solutions, the quantities and quality of salts, the quality of water (the degree of chlorination is checked), are strictly followed, and it is advisable to measure the electrical conductivity (EC) and pH of the nutrient solution before use in hydroponic installations *(Papadopoulos et al., 1999).*

The concentration of dissolved nutrients in the nutrient solution determines the electrical conductivity (EC), a physical quantity associated with the nutrient solution's ability to allow the passage of an electric current, measurable with a conductometer. As the concentration of solute ions increases, the electrical conductivity also increases. As units of measurement, electrical conductivity can be expressed in Siemens (S) or the mho equivalent (the inverse of the Ohm value), *(Resh, H. M., 2022).* The conductivity of the nutrient solution depends, first of all, on the presence of salts dissolved in the water, but also on the water temperature. Pure water has a very low conductivity, of only 0.0055 µmho, drinking water from groundwater has a conductivity between: 30 and 2000 µmho, while ocean and salt sea waters have a high conductivity between: 45000 and 55000 µmho. *(Savvas, D., & Passam, H. C., 2002)*.

Another related measurement is TDS (total dissolved solids); it represents the total amount of dissolved solids in a solution. Because dissolved solids in the form of ions, such as salt and minerals, contribute to the conductivity of a solution, the TDS meter initially measures the electrical conductivity of the solution, then converts the recorded data into a value that can be read on the meter's liquid crystal display, according to an approximate relationship: TDS <mg/l> = EC <µS/cm> * k; k= 0.67; 1 mg/l= 1 ppm The unit used by most TDS meters is expressed in parts per million (ppm) or mg/l.

The role of the growth medium is only to support the root system. The materials that make up this medium must meet a series of qualitative criteria (according to Verguiero Martins, (*www.hydor.eng.br):* be chemically inert; be insoluble in the nutrient solution; be biologically sterile and easy to handle;have a neutral

pH or as close to this value as possible;ensure aeration and drainage of the roots, maintaining a constant and equal ratio of air and water;prevent root infestation;ensure adequate retention of water, oxygen and nutrients; be sterilized, if reused, or recyclable, if not reused;have a granulation and texture appropriate for the cultivated species, its root and its size;be inexpensive and easy to obtain.

The aforementioned requirements are met by a series of materials specially selected and tested for horticultural use, many of which have established commercial names *(Wang, S., Zhou, L., & Liu, P. 2024):*

- Perlite. It is a very porous volcanic rock, with a low specific gravity, which has a high air retention capacity. For this reason, it is a very good medium for aeration, not being used to drain excess nutrient solution. The most advanced commercial product made from perlite is called Aerolit.
- Vermiculite. It is a volcanic rock with less porosity (spongy volcanic glass), which does not allow rapid evaporation of water. Water and dissolved nutrients are retained in the rock and drained much more efficiently towards the plant's root system. It does not allow good aeration of the roots.
- Rockwool (mineral wool for horticultural use). It is a product made of long and thin threads, drawn from molten rock. The threads are then packed and pressed. It is a completely sterile medium, more difficult to handle.
- Coconut coir fiber (fiber extracted from the fruits of Cocos nucifera). It is an organic, completely recyclable growing medium, based on the extraction of fibers from coconuts. The retention properties, both for water and air, along with the high content of antifungal substances and growth hormones, recommend this growing medium in top hydroponic applications.
- Gravel, slag. Made by selecting gravel and slag pieces of appropriate size. They represent inexpensive solutions, the medium however having the disadvantage of being able to induce a change in the pH of the nutrient solution.
- Hydroton (LECA-Lightweight Expanded Clay Aggregate) consists of clay granules, fired at temperatures of 1200-1300 0C and subjected to an expansion process, thus becoming very porous. They have a diameter between 8-16 mm, are chemically inert, with a neutral pH, present a high level of nutrient solution loading and have a low cost, *(Raviv, M., & Lieth, J. H., 2008).*

Hydroponic system lighting. A convenient performance/cost ratio recommends the current use of plant lighting with Light Wave T5 fluorescent lamps (Fluorescent Plant Lighting). This type of lighting generates faster growth and strong development of the leaf system, the formation of short internodes and thick stems. The spectral response (towards the red and blue portion of the spectrum) has proven to be beneficial for cultivated plants, under conditions of very low secondary thermal emission.These lamps thus allow positioning in close proximity to the plants (at approximately 25-50 cm from the growth vessels), using the emitted luminous flux very efficiently, *(Zúñiga, R. S., & Campos, A., 2024*). The stability of the luminous flux is approximately 15,000 hours, ensuring continuous operation for 18 months, with a decrease in luminous flux of only 20%. The length of the fluorescent tube (600 mm) distributes the light flux evenly and linearly towards the cultivated plants, *(Al-Kodmany, K., 2023).*

Temperature. In all these systems, the optimum temperature must be ensured (both in the nutrient solution and in the air), a temperature characteristic for each cultivated species. Increasing the temperature accelerates the vegetative development of the plant, but also its water requirement. The regulation and maintenance of the appropriate temperature is carried out using thermostats equipped with temperature sensors and heating elements, *(Ahmed, K., & Rahman, M., 2024).*

Air. The movement of air masses and its oxygen and carbon dioxide content constitute key factors with a great influence on the quality of the obtained vegetable products. As main physiological processes determined by this factor, we can refer to: water consumption, appropriate lignification of the stem and flower stalks, pollination, fruit ripening, biomass production. The control of these processes is achieved by the movement of air masses using fans (controlled in speed and position) and external fresh air intakes, monitoring and regulating the carbon dioxide content, *(Benke, K., & Tomkins, B.,2022).*

RESULTS

The analysis of hydroponic culture systems and classical agricultural technologies highlighted a series of general aspects, resulting from the comparison of qualitative and quantitative indices, correlated with the production process and the productivity of the obtained crops.

The results of the comparisons between classical agricultural technologies and the hydroponic method of plant cultivation are summarized in Table 1, *(Bhattarai, G. P., et al., 2023).*

Table 1

Hydroponic systems and classical agricultural technologies.

Hydroponic systems	Classical agricultural technologies
It does not require solid culture media, being sufficient the partial immersion of the plant's root system in the nutrient solution.	The soil (culture medium) is reused, fertilized and treated, with each reseeding and planting.
Can keep plants alive and fresh for a long time.	The plant dies when removed from the soil.
They can be achieved without the presence of soil (even in outer space).	The quality and properties of soil essentially influence the quantity and quality of agricultural production.
They allow complete control of the plant and its root system.	They only allow observation of the root system by extracting the plant from the soil.
The plant is transferable to any place (for study and research purposes).	The plant is tied to the place of growth (in field crop plots).
The amount of water required for plant growth and development is used with maximum efficiency and efficiency.	Field cultivation requires large amounts of water, which is used with low efficiency in irrigation systems.
It does not require pesticides, the isolated growing environment and especially the lack of soil, limiting the spread of weeds and pests.	The presence of soil, open spaces and proximity to other crops easily spread weeds and pests.
It represents a clean, ecological technology, with high quality agricultural products.	Classical agricultural technologies require the use of fertilizers, chemical substances to control pests, herbicides
Hydroponic technology under controlled conditions extends growing seasons and removes the constraints related to the current trend of global climate change.	Agricultural production is strictly linked to location, climatic conditions, growing season, and unforeseen meteorological events.
A hydroponic system is suitable for complete automation and control using local or remote computing systems.	Classical agrotechnics, carried out in specific locations and conditions, do not allow for complete automation.
Stability, predictability, safety and exceptional productivity of crops.	Unstable, unpredictable, their productivity being dependent on the conditions in which the agricultural crop is carried out.

The average productivity of hydroponic technologies is at least 20-25% higher than classical agricultural technologies, in conditions of maximum efficient use of space, water and other resources. An important aspect of nutrient solutions is that they contain ions in a dissolved state, in chemical forms that can be easily absorbed by plants, for this reason the productivity of hydroponic systems is closely correlated with the bioavailability of nutrient solutions and the careful regulation of their pH, *(Cho, Y., et al., 2023).* The use of process computers, sensors and the development of automatic regulation and control systems of all parameters involved in hydroponic systems increase the accessibility of these technologies. The use of solar power systems, the use of light-emitting diode (LED) lighting and solar thermal panels represent methods for further increasing economic efficiency in hydroponics, *(Dinesh, R., et al., 2023).*

Sanitary issues and disease management. Hydroponic systems, especially recirculating systems, can promote the rapid spread of pathogens (Pythium, Phytophthora, bacteria). Preventive measures include: Water filtration and treatment (UV, ozonation, mechanical filters). Temperature and DO control to limit conditions favorable to pathogens, *(Eissa, M. A., 2022).* Hygiene practices: periodic sterilization of the tank and components, quarantine of new plants. Regular microbiological monitoring. Recent research is exploring biological strategies (biostimulants, beneficial microbes) for disease control instead of harsh chemical solutions, but commercial adoption is still developing, *(El-Mahdy, M. et al., 2024, Jang, Y., et al., 2024).*

Sustainability and environmental impact. Hydroponics reduces land degradation and uses water more efficiently; however, there are environmental considerations: Energy consumption: artificial lighting (LED) and air conditioning can increase the energy footprint; the use of renewable energy can mitigate this impact. Nutrient solution management: uncontrolled discharges can cause eutrophication; best practices involve treating/recycling solutions and minimizing losses. Materials and waste: substrates and plastic components must be managed responsibly (reuse, recycling), *(Furlan, C., & Trevisan, M. 2024).* Life cycle assessments (LCA) show that hydroponics can be more sustainable in urban contexts (reduction of transport, local supply) but the situation varies depending on the energy source and the efficiency of the system.

Conceptually, the theoretical importance of hydroponics lies in its ability to provide a controllable and reproducible system for studying plant physiology. In the absence of soil, researchers can precisely manipulate environmental variables – pH, electrical conductivity, ionic ratios, temperature, dissolved oxygen – and directly observe the metabolic and morphological responses of plants. This experimental setting provides a deeper understanding of the relationships between mineral nutrition and physiological processes, such as photosynthesis, respiration, or biomass formation, *(Han, J., et al., 2023).* As a result, hydroponics has become an essential scientific tool for developing predictive models of plant growth, testing biostimulants, microbial inoculants, and abiotic stress reduction strategies. It contributes to the development of an experimental plant ecology that transcends the limitations of soil, providing quantitative data useful in both fundamental biology and applied agronomy, *(González, M. P., et al., 2023)*.

From a technological perspective, hydroponic systems reflect one of the most advanced forms of precision agriculture. The integration of sensors, automation and artificial intelligence allows for the continuous monitoring of essential parameters of the growing environment, offering the possibility of automatic adjustment of nutritional recipes and microclimatic conditions. This digitalization of the agricultural process represents not only an operational progress, but also an epistemological transformation of the way in which the relationship between plants and their environment is understood and managed. Hydroponics thus becomes an expression of smart agriculture – a cybernetic system in which data, feedback and machine learning contribute to a dynamic optimization of resources, *(Kim, S., & Park, J., 2025).* These innovations transform hydroponic farms into models of efficiency, in which every liter of water, every kilowatt of energy and every gram of nutrients are accounted for and rationally utilized, *(Li, F., et al., 2025).*

Another fundamental aspect of the relevance of hydroponics is its potential to respond to the challenges of urbanization and food security. Urban hydroponic farms and vertical production systems allow the cultivation of vegetables, fruits and aromatic plants directly in consumption centers, reducing logistics costs, post-harvest losses and the carbon footprint associated with transportation, *(Li, F., et al., 2025).*

At the same time, these systems can operate in unconventional spaces – industrial buildings, containers, basements – transforming the urban environment into a new agricultural space. From a social point of view, hydroponics contributes to democratizing access to fresh food and strengthening the resilience of urban communities in the face of supply fluctuations, *(Mehra, S., et al., 2025*).

CONCLUSIONS

Scientifically, the future of hydroponics depends on advances in several converging directions. One of these is molecular biology and genetics, which allows the development of varieties optimized for hydroponic environments – plants with root systems adapted to limited oxygenation, with high efficiency in ion absorption or with increased capacity to use artificial light. Another major direction is the integration of data sources and artificial intelligence algorithms for real-time prediction of nutritional requirements and for automatic optimization of the environment. In parallel, a trend is emerging towards ecological hydroponics – the use of organic nutrient solutions, natural biostimulants and beneficial microorganisms, which can transform these systems into a form of regenerative and fully sustainable agriculture.

The relevance of the topic is amplified by the current global context, in which there is intense discussion about the resilience of food systems. Pandemics, geopolitical conflicts and extreme climate events have highlighted the vulnerability of traditional supply chains. In this context, hydroponics appears as a strategic solution – a decentralized, modular and controllable food infrastructure that can operate almost independently of external conditions. By reducing dependence on soil and climate, these systems contribute to national and regional food security, offering the possibility of producing food in any environment, from arid areas to space stations.

Thus, the study, development and implementation of hydroponic systems is not just a technological exercise, but a strategic investment in the future of food and society. Hydroponics combines the fundamental principles of plant biology with engineering innovation and the ecological imperatives of the 21st century, generating a space of convergence between science, economics and ethics. In a world where resources are becoming limited and the global population continues to grow, its importance can no longer be seen as an option, but as a necessity. Hydroponics therefore becomes not just an agricultural technology, but an expression of humanity's adaptive intelligence — a bridge between scientific knowledge and long-term sustainable survival.

In conclusion, the theoretical and applied importance of hydroponics derives from the intersection of science, technology and sustainability. It redefines the concept of agriculture by transferring control from

nature to human intelligence, without breaking the ecological balance, but trying to reproduce and optimize it. By finely controlling resources, reducing losses and integrating biological knowledge, hydroponics offers a vision of the future of agriculture – one characterized by precision, efficiency and ecological responsibility. From this perspective, it is not just an alternative to traditional agriculture, but a model for the transition towards an agriculture of knowledge, circularity and sustainability.

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THE IMPACT OF DISRUPTIVE FACTORS ON THE SUSTAINABILITY OF VEGETABLE PRODUCTION IN THE TECUCI AREA

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ABSTRACT

The Tecuci vegetable-growing area stands out for its high agricultural potential for vegetable crops, thanks to a favorable combination of natural (soil, climate) and socio-economic (tradition, agricultural infrastructure) factors, which create conditions conducive to vegetable growing. However, this area also faces a number of disruptive factors that can compromise the sustainability of vegetable production. The purpose of this paper is to identify and analyze the main disruptive factors affecting the sustainability of vegetable systems in this area. The research was based on a field study conducted in 12 localities in the Tecuci vegetable-growing basin, Galati County, by applying a standardized questionnaire to a sample of 278 respondents. The results highlight the need to adopt practices to mitigate the negative impact of the identified factors, including the use of organic fertilizers (e.g., compost), the application of appropriate crop rotation and crop rotation, the selection of cultivars with high stress tolerance, and investment in modern and efficient irrigation systems for vegetable crops.

REZUMAT

Bazinul legumicol Tecuci se remarcă printr-un potențial agricol ridicat pentru culturile legumicole, datorită unei combinații favorabile de factori naturali (sol, climă) și socio-economici (tradiție, infrastructură agricolă), care creează condiții propice pentru practicarea legumiculturii. Cu toate acestea, această zonă se confruntă și cu o serie de factori perturbatori care pot compromite sustenabilitatea producției legumicole. Lucrarea de față are ca scop identificarea și analiza principalilor factori perturbatori care afectează sustenabilitatea sistemelor legumicole din această zonă. Cercetarea s-a bazat pe un studiu de teren desfășurat în 12 localități din Bazinul legumicol Tecuci, județul Galați, prin aplicarea unui chestionar standardizat unui eșantion de 278 de respondenți. Rezultatele obținute evidențiază necesitatea adoptării unor practici pentru diminuarea impactului negativ al factorilor identificați, printre care se numără utilizarea îngrășămintelor organice (ex. compost), aplicarea unui asolament adecvat și a rotației culturilor, alegerea cultivarelor cu toleranță ridicată la stres, precum și realizarea de investiții în sisteme moderne și eficiente de irigare a culturilor legumicole.

INTRODUCTION

The Tecuci vegetable basin is considered particularly favorable for vegetable cultivation due to a combination of natural and socio-economic factors *(Chiran et al., 2004).* The assessment of these factors requires an integrated approach. Periodic soil and water analyses, continuous control of pests, pathogens, and weeds, as well as assessment of weather conditions are *recommended (Stoleru et al., 2008; Bireescu et al., 2010)*. Early diagnosis of problems allows for the application of effective preventive and corrective measures adapted to specific conditions *(Popa, 2010).*

To reduce the effects of disruptive factors, a series of solutions can be adopted to ensure the sustainability of vegetable production. These include the use of organic fertilizers, such as compost or well-fermented manure, crop rotation, the selection of cultivars resistant to disease and abiotic stress, and the

use of efficient irrigation methods, such as drip irrigation *(Munteanu et al., 2008b; Stoleru et al., 2008)*. Sustainable agriculture is becoming increasingly important in this context *(Munteanu et al., 2008a; Basso et al., 2020)*.

The sustainability of vegetable production is a fairly common topic in all fields, such as economics, science, politics, as well as in agricultural practice in our country *(Mușcalu et al., 2020; Brumă et al., 2021; Prigoreanu et al., 2025)*. Sustainable vegetable production is both a necessity and an opportunity *(Stoleru, 2008; Teliban, 2011)*.

This is a necessity, because the degradation of intensive and super-intensive vegetable ecosystems, soil pollution, and plant and crop contamination are risks that we must not take in the name of agricultural progress; this can be achieved without harming ourselves *(Leza et al., 2021; Lu et al., 2021).*

Sustainable vegetable production is an opportunity, as more and more people, aware of the nutritional value of vegetables, prefer products obtained in agricultural systems with low chemical inputs *(Radulescu et al., 2021; Matache et al., 2024)*. At the same time, although vegetables are recommended for everyone along with fruit, they are strongly recommended for certain target consumer groups: children, the elderly, and sick people *(Teliban et al., 2009; Wang et al., 2014; Vintilă et al., 2021).*

Taking into account the needs and opportunities, the purpose of this study is to determine the extent to which it is possible to promote the sustainability of vegetable farming in the Tecuci vegetable-growing basin.

MATERIALS AND METHODS

The proposed study was conducted using questionnaires specifically designed to examine disruptive factors that may affect the sustainability of vegetable production in the Tecuci area. These types of studies are usually conducted on appropriate samples of respondents so that the responses obtained reflect as accurately as possible the theoretical average values of the population under investigation *(Stoleru, 2008*). As part of this research, 278 people were interviewed between 2024 and 2025.

The questionnaire was developed based on an extensive bibliography in the field *(Buia et al., 2003; Miftode et al., 2005; Raisa, 2008).* The questionnaire used in this study comprises 18 questions and is divided into four sections.

The first section covers general information about the interviewees, such as the location of the vegetable farm, the cultivated area, the growing environment (open field, greenhouse, or mixed), the main vegetable species grown, and the vegetable growers' experience in the field.

The second section covers disruptive factors (drought, diseases and pests, weeds, frost, input costs) and their impact on sustainable vegetable cultivation.

The third section refers to the agricultural practices used by vegetable growers to prevent and combat disruptive factors (treatments carried out, fertilizers used, irrigation, soil analyses).

The last section of the questionnaire refers to sustainability and access to resources (training courses or projects on organic/sustainable agriculture, European funds or APIA aid, interest in more environmentally friendly solutions, obstacles encountered in applying sustainable practices).

Processing statistical data and interpreting it

The processing of statistical data ensures the possibility of making comparisons, revealing differences and their significance. Respondents' answers were verified, validated, and processed using specific methods via Google Forms. Following validation, 260 of the 278 questionnaires used were deemed valid (with complete answers to all questions, answers within acceptable limits/"serious answers").

RESULTS

I. Results regarding the distribution of respondents

Analysis of the validated questionnaires showed that, out of a total sample of 260 vegetable growers, 102 respondents (39%) came from the commune of Cudalbi, 70 (27%) from Matca, and 26 (10%) from Corod. The other participants are distributed in neighboring localities in Galați County, such as Tecuci, Grivița, Valea Mărului, Pechea, Ivești, Barcea, Adam, and others (Fig. 1). These areas are known for their tradition in vegetable growing, with Matca standing out at the national level through the intensive development of the horticultural sector and its significant contribution to vegetable production in Romania.

In terms of farm size, areas cultivated with vegetables range from less than 0.5 hectares to more than 2 hectares, reflecting, in most cases, a family-type agriculture with small farms. This structure suggests efficient use of available land and a focus on high-value crops, mainly for local and regional markets. The

distribution of respondents according to cultivated area shows that over 60% of vegetable growers farm land smaller than 0.5 ha, 24% cultivate between 0.5 and 1 ha, 10% work between 1 and 2 ha, and only 6% have vegetable areas larger than 2 ha.

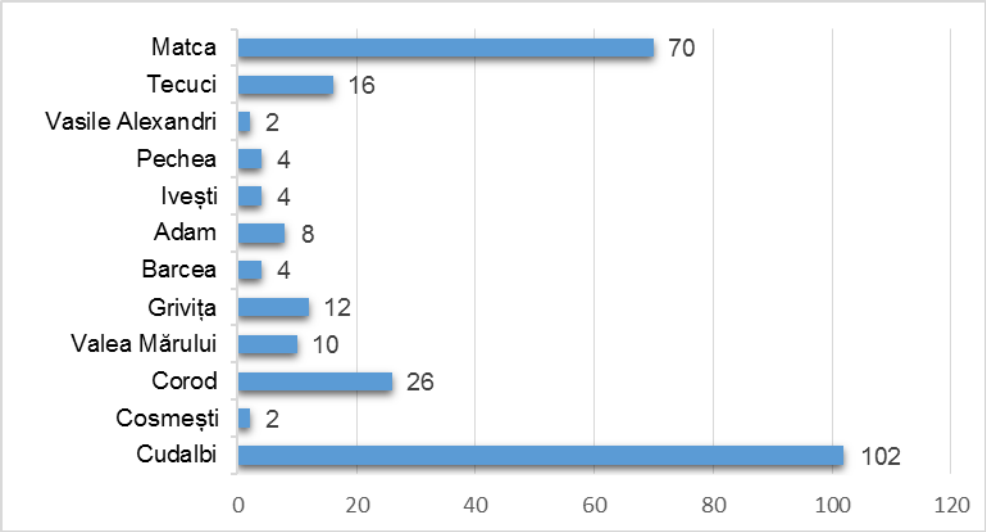

Fig. 1 - Municipalities where the questionnaires were administered

Most respondents stated that they grow vegetables in protected systems, predominantly in greenhouses (40%), followed by mixed systems (greenhouses and fields – 21%) and hothouses (6%). The choice of these forms of cultivation is motivated by the obvious advantages they offer: extension of the growing season, protection against extreme weather events, and ensuring early and consistent production. Open field cultivation is practiced by approximately 33% of vegetable growers, while the use of greenhouses remains limited, due to the high costs involved, which make it accessible only to a small number of producers.

In terms of the structure of the vegetable assortment, the data obtained shows a clear dominance of tomato cultivation, grown by 208 of the respondents. This species is followed, in descending order, by cucumbers (138 respondents), peppers (124 respondents), eggplants (88 respondents), and, in significantly smaller proportions, cabbage (44 respondents), green beans (42 respondents), lettuce (20 respondents), and melons (8 respondents). There is thus a clear preference for species that are in high demand on the market, but also well adapted to local soil and climate conditions and to the technologies used in protected cropping systems (Fig. 2).

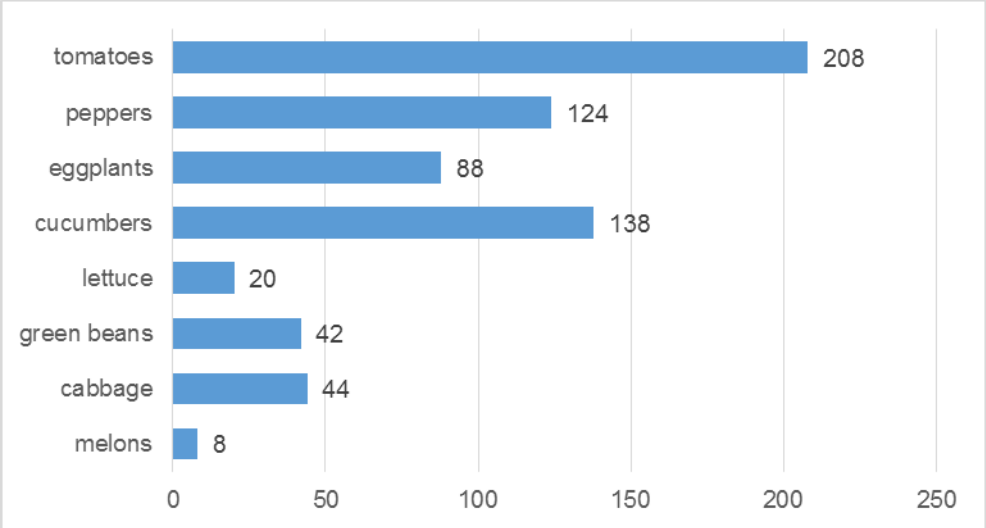

Fig. 2 - The main vegetable species grown by respondents

The level of experience of respondents in vegetable growing is relatively high, with 37.7% stating that they have been active in this field for over 10 years and 20.8% having between 5 and 10 years of experience. The remaining respondents, representing 41.5%, have less than 5 years of experience. These

results reflect a good practical knowledge of cultivation technologies among the majority of farmers interviewed, but also highlight the need to continue the training process, especially in the context of adapting to climate change and the transition to sustainable agricultural practices.

II Results regarding disruptive factors

Over the past three years, most of the vegetable growers surveyed reported significant difficulties caused by prolonged drought (mentioned by 196 respondents), pest attacks (162 respondents), and the presence of pathogens (124 respondents), These problems are perceived as the most serious threats to vegetable crops in the area. The lack of regular rainfall, combined with high temperatures, has affected plant development, especially during the critical stages of flowering and fruiting.

In addition to these major factors, respondents also reported other difficulties, such as the high costs of inputs (seeds, plant protection products, fertilizers), but also the negative impact of late spring frosts, which have been frequently observed in recent years. These problems were particularly acute in the localities of Matca, Corod, and Cudalbi, where vegetable farming is widespread.

Another major disruptive factor identified was the presence of the *Tuta absoluta* insect, an aggressive pest of tomato crops, which caused considerable losses in protected areas. Controlling it is difficult using conventional methods, which leads to the frequent use of phytosanitary treatments, which are often costly and have possible negative effects on the environment. Other pests, such as thrips, aphids, nematodes, and mites in cucumber crops, were also mentioned in the questionnaire responses, but with lower frequency.

III Results regarding agricultural practices used

Among the most common diseases affecting vegetable crops, farmers mentioned mildew, leaf rust, brown spot, and fusarium wilt, which are considered to have a significant economic impact on production.

Most of the vegetable growers surveyed stated that they use chemical treatments, biological treatments, and crop rotation to combat diseases and pests, with each method being applied by a significant number of respondents (over 100). The high frequency of use of these methods is explained by their immediate effectiveness and ease of application. However, only a small number of farmers indicated the use of complementary methods, such as pheromone traps or the association of crops with repellent species. These responses indicate a moderate openness to sustainable control techniques, but also a clear need for additional training and information among producers.

In terms of the impact of these disruptive factors on production, over 38% of farmers estimated losses of between 10% and 30%, and 41.5% reported losses of more than 30%. These figures highlight the high vulnerability of the current vegetable production system to the pressures exerted by climate change and biotic factors, such as pathogens and pests.

In fact, most respondents confirmed their perception of significant climate change in recent years, manifested by changes in precipitation patterns, longer periods of drought, and more frequent extreme events, such as late spring frosts.

The fertilization of vegetable crops is mainly based on the use of manure, chosen by 66.2% of respondents as the main source of nutrients. A smaller percentage of farmers said they use chemical fertilizers (18.5%) or compost (7.7%), which indicates, in some cases, a trend towards semi-organic fertilization. However, the use of compost remains very limited, possibly due to low accessibility or lack of information. In addition, 7.7% indicated that they do not apply any form of fertilization, a situation that can be explained by insufficient financial resources or lack of specialized knowledge in the field of vegetable growing.

Drip irrigation is the predominant option among the vegetable growers surveyed, being used by over 77% of them, especially in protected areas. This system is appreciated for its high efficiency in water use, which is essential in the current context of climate change. Manual watering is used exclusively on very small farms, and sprinkler irrigation is extremely rare (2.3%). A small percentage, 7.7% of respondents, said they do not use any form of irrigation, which can contribute significantly to production losses during periods of drought.

Soil analysis remains an insufficiently implemented practice. Only 18.5% of farmers perform annual analyses, and 15.4% do so every few years. Over 35% of respondents indicated that they do not carry out this activity at all. The lack of monitoring of fertility parameters can lead to the inappropriate application of fertilizers and, consequently, to the progressive degradation of soil quality in the long term.

IV Results on sustainability and access to resources

Farmers' participation in courses or projects dedicated to organic/sustainable agriculture is relatively limited. Approximately 49.7% of respondents said they had received formal training, while over 18% had obtained information through informal channels, such as direct discussions with other farmers or materials available online. These results highlight a clear need for organized, structured, and accessible training tailored to the real needs of producers.

In terms of access to financial resources, only 30.8% of farmers have benefited from European funds, used mainly for investments in agricultural infrastructure. A smaller percentage, 8.5%, expressed their intention to access such funding in the future, suggesting significant potential for development in this direction. In addition, most respondents said they participate in the national Tomata program, which is seen as essential support for maintaining activity in difficult economic conditions.

With regard to openness to environmentally friendly agricultural practices, over 81% of farmers said they were interested in adopting them, and 16% indicated partial interest. However, the actual application of these practices is still limited due to high costs, lack of concrete information, and instability in the vegetable market.

The opinions expressed in the comments section of the questionnaire highlighted the need to create a secure market for vegetable products, provide specialized agricultural advice, easier access to EU financial support, and subsidies for large-scale irrigation or to cover damage caused by extreme weather events.

CONCLUSIONS

The study highlights a predominance of small, family-run vegetable farms concentrated in the communes of Matca, Cudalbi, and Corod, areas with a recognized horticultural tradition. Vegetable growing takes place mainly in protected areas, with a clear focus on high-demand species such as tomatoes, peppers, and eggplants.

Although a considerable proportion of farmers have more than 10 years of experience, there is still a need for continuous training, particularly in integrated pest management, adaptation to climate change, and the application of sustainable practices.

The most frequently mentioned disruptive factors are drought, pests, and diseases, which often lead to losses of over 30% of production.

In this context, the predominant use of manure and drip irrigation reflects a concern for efficiency, but soil analysis remains a rare practice.

Participation in courses and projects is limited, and access to European funds is still low, although there is interest in development. Farmers are open to sustainable methods, but their application is restricted by costs, lack of information, and market instability for vegetable products.

To strengthen the sustainability of the vegetable sector, integrated support is needed: specialized training, support for access to resources and financing, mechanisms to protect against climate risks, and the development of stable and functional markets.

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ANALYSIS OF INSTANTANEOUS ELECTROMAGNETIC POWER DENSITY AND ITS IMPACT ON HONEYBEE COLONIES IN THE VICINITY OF GSM ANTENNAS (0–500 m)

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ANALIZA DENSITĂȚII INSTANTANEE DE PUTERE ELECTROMAGNETICĂ SI A EFECTELOR ASUPRA COLONIILOR DE ALBINE AFLATE IN PROXIMITATEA ANTENELOR GSM (0–500 M)

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Keywords: *honey bees, electromagnetic radiation*

ABSTRACT

Electromagnetic radiation from modern technologies, especially 4G/5G antennas, may affect living organisms. This study examined the impact of electromagnetic pollution on honey bee colonies by correlating field intensity with behavioral and physiological changes. Research was conducted in three southeastern Romanian apiaries: Vrancea and Ialomița (affected) and Argeș (control), all within 500 m of GSM antennas. Electromagnetic field measurements and biological monitoring revealed strong spatial variation. Peaks of 37.99 mW/m² (Vrancea) and 39.05 mW/m² (Ialomița) were linked to disorientation, agitation, reduced flight, and mortality. In contrast, the Argeș apiary showed lower exposure (< 0.30 mW/m² at 500 m) and maintained colony health. Findings suggest that elevated or reflected EMF levels can alter bee activity, emphasizing the need for continuous monitoring near apiaries.

REZUMAT

Radiațiile electromagnetice provenite din tehnologiile moderne, în special de la antenele 4G/5G, pot afecta organismele vii. Acest studiu a analizat impactul poluării electromagnetice asupra coloniilor de albine, corelând intensitatea câmpului electromagnetic cu modificările comportamentale și fiziologice. Cercetarea a fost realizată în trei stupine din sud-estul României: Vrancea și Ialomița (afectate) și Argeș (martor), amplasate la distanțe de până la 500 m față de antenele GSM. Măsurătorile câmpului electromagnetic și monitorizarea biologică au evidențiat o variație spațială semnificativă. Vârfurile de 37,99 mW/m² (Vrancea) și 39,05 mW/m² (Ialomița) au fost asociate cu dezorientare, agitație, reducerea zborului și mortalitate. În contrast, stupina din Argeș a prezentat o expunere mai redusă (< 0,30 mW/m² la 500 m) și a menținut starea de sănătate a coloniilor. Rezultatele sugerează că nivelurile ridicate sau reflectate ale câmpurilor electromagnetice pot modifica activitatea albinelor, subliniind necesitatea unei monitorizări continue în apropierea stupinelor.

INTRODUCTION

Electromagnetic radiation emitted by modern technologies—mobile phones and 4G/5G communication antennas—can adversely affect the behavior and physiology of exposed organisms (*Ratnieks et al., 2010*), including honeybee colonies (*Cucurachi et al., 2013*). Alongside conventional stressors such as pesticides and intensive agriculture, recent research identifies electromagnetic radiation as a complementary factor in insect decline. Balmori et al. (2021) emphasized that electromagnetic field effects, documented for over five decades, may act synergistically with other stressors, reducing pollinator diversity and abundance. A meta-analysis by Cucurachi et al. (2013) showed that radiofrequency electromagnetic fields (RF-EMF) can influence multiple taxa and ecological processes, though impacts on insects, particularly pollinators, remain insufficiently characterized. Similarly, Vanbergen et al. (2019) evaluated anthropogenic EMF risks for pollinators, revealing major knowledge gaps and stressing the need for controlled experimental research under real environmental conditions.

The first experimental evidence originated from laboratory studies. Westerdahl and Gary (1981a) reported reduced longevity and altered food intake in bees exposed to 2.45 GHz microwaves, and later (1981b) described impairments in flight, orientation, and homing ability, indicating physiological and

behavioral disruption. Subsequent studies confirmed these findings: Harst et al. (2006) observed behavioral alterations under EMF exposure; Kumar and Sangwan (2011) demonstrated biochemical changes in worker bees exposed to mobile phone radiation; and Sahib et al. (2011) recorded decreased colony density near mobile phones. Later research strengthened this evidence—Migdał et al. (2021) reported long-term 50 Hz exposure affecting the proteolytic system and behavior; Odemer et al. (2019) showed RF-EMF interference with queen development and mating success; and Vilić et al. (2024) identified oxidative stress responses at 900 MHz. Szychta et al. (2024) synthesized multiple EMF-induced effects on worker behavior and physiology. Together, these results support a multifactorial view of colony decline (*Ratnieks et al., 2010*), where electromagnetic radiation acts synergistically with other stressors such as pesticides and climate change (*Migdał et al., 2024*). Evaluating EMF impact on honeybee colonies is therefore essential for understanding biological risks and applying the precautionary principle.

The aim of this study is to evaluate the potential effects of exposure to non-ionizing electromagnetic radiation on the health of honey bee colonies. The research focuses on correlating electromagnetic field (EMF) intensity with behavioral and physiological changes in colonies, through a comparative approach between exposed and control areas. This monitoring allows the identification of potential risks associated with mobile communication infrastructure and provides a framework for applying the precautionary principle in pollinator protection.

MATERIALS AND METHODS

Experimental design – selection of locations and apiaries, identification of emission sources (GSM antennas)

The study was conducted by a research team from the National Institute for Research and Development in Plant Protection, Bucharest (44°30'05.0"N 26°04'14.5"E), in collaboration with specialists from the National Institute of Research and Development for Machines and Installations Designed for Agriculture and the Food Industry, Bucharest (44°29'57.8"N 26°04'21.5"E).

The research group collaborated with independent beekeepers who voluntarily agreed to participate in the study. Three private apiaries were selected for investigation, each located approximately 500 m from EMF emission sources (GSM antennas), in the following areas: Vrancea (45°33'10.2"N 27°06'30.3"E) – STP 1, Ialomița (44°44'43.4"N 26°35'08.3"E) – STP 2, and Arges (45°11'50.0"N 25°00'26.2"E) – STP 3.

During the inactive season of 2023, the experimental groups were established as follows: 59 honeybee colonies formed the experimental lot (40 in VN-STP 1 and 19 in IL-STP 2), while the control lot included 85 colonies from AG-STP 3. Laboratory examinations followed World Organization for Animal Health *(OIE, 2013)* standards. Based on anamnesis data regarding colony history, environment, and previous interventions, six monitoring records and six laboratory reports were completed (one per apiary and season). Morpho-clinical evaluations were then conducted through visual inspections to identify abnormal behavior, morphological changes, or flight deviations (Table 1).

Table 1

General data on the monitored apiaries and associated documentation

Apiary / County	Evaluation distance antenna–apiary (m)	Area type	EMF source	Number of colonies at the beginning of the experiment	Monitoring records 2024–2025	Analysis reports issued 2024–2025
VN STP 1	at the antenna base, 10, 100, 200, 300, 400, 500	rural	Wi-Fi, moderate EMF	40	2	2
IL STP 2		rural	Low EMF	19	2	2
AG STP 3		submontane	Possible mixed EMF sources	85	2	2

The distance between the electromagnetic radiation source (telecommunication antenna) and the apiaries was determined using a GPS application with satellite maps. Measurement points were established at the antenna and at 100 m intervals up to 500 m to capture exposure (Figure 1**).**

These reference points supported the correlation between field intensity and possible physiological or behavioral effects in honeybee colonies. Accurate distance measurement ensured data standardization and consistent evaluation of non-ionizing field influence. Between 2024 and 2025, power density was measured using specialized instruments: EMF Meter Extech 480846 (mW/m², 10 MHz–8 GHz), sound level meter (dB, °C, U%), and spectrum analyzer UNI-T UTS1032T (9 kHz–3.2 GHz) **(**Figure 2**)**.

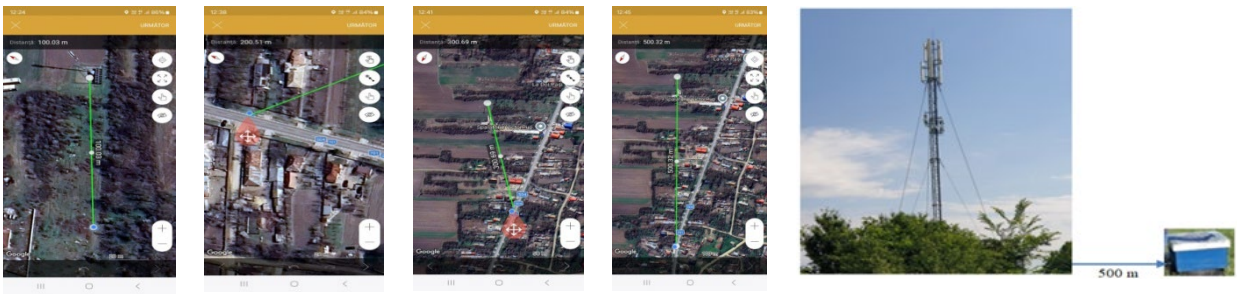


Fig. 1 - Distance between the GSM antenna and the apiary, determined by GPS coordinates, within the 10–500 m range

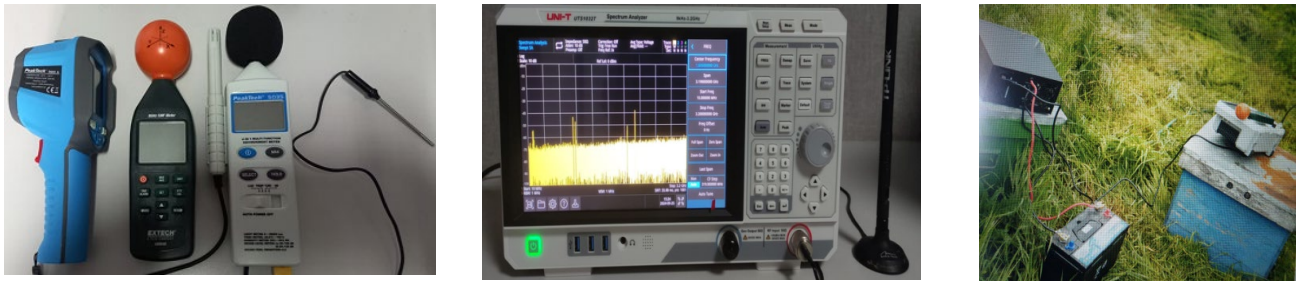


Fig. 2 - Thermal camera (°C), EMF Meter Extech 480846 (mW/m²), sound level meter (dB, °C, U%), spectrum analyzer UNI-T UTS1032T

RESULTS

Maximum values of electromagnetic field intensity measured in 2024 and 2025 at different distances from the GSM antenna in the apiary locations from VN, IL, and AG counties

The maximum values of electromagnetic field intensity measured in 2024 and 2025 at different distances from the GSM antenna in the locations from VN, IL and AG counties, highlighting the temporal and regional variations of exposure in the proximity of the apiaries, are presented in Table 2.

Table 2

Comparison of maximum electromagnetic field intensity values (mW/m²) as a function of distance from the 4G antenna, for the years 2024 and 2025, in the locations from VN, IL and AG counties

Measurements [mW/m²]	2024			2025		
	VN STP 1	IL STP 2	AG STP 3	VN STP1	IL STP 2	AG STP 3
at the antenna base	1.71	26.07	14.94	8.89	6.71	10.3
10	4,00	15.81	9.26	37.99	9.83	7.54
50	5.93	11.87	4.70	3.06	6.48	7.44
100	11,51	26.37	5.50	4.55	4.21	5.52
200	11.02	124.40	1.34	4.23	6.83	4.54
300	4.93	96.93	1.93	3.11	41.87	5.87
400	2.13	4.59	1.06	6.43	45.98	3.11
500	2.72	2.17	1.06	3.98	5.37	1.07

The comparison of maximum electromagnetic field intensity values recorded in 2024 and 2025 at different distances from the 4G antenna shows clear spatial and temporal variations. In VN (STP 1), values rose markedly in 2025, especially at 10 m-from 4.00 to 37.99 mW/m²-indicating possible emission increases or infrastructure changes.

At greater distances (100–500 m), levels slightly decreased or remained moderate. In IL (STP 2), the trend was opposite: extremely high values in 2024 (124.40 mW/m² at 200 m; 96.93 mW/m² at 300 m) dropped in 2025, suggesting antenna reconfiguration or reduced local reflections. Still, exposure at 300–400 m (41.87–45.98 mW/m²) stayed high, beyond expected safe limits. In AG (STP 3), 2025 values were balanced and stable -7.54 mW/m² at 10 m, under 1.1 mW/m² at 500 m showing more consistent and controlled emissions.

Overall, 2025 data reveal higher exposure near antennas in VN and persistent elevated values in IL, while AG remained electromagnetically stable. Such intensified fields may affect bee colonies by disrupting orientation and flight activity.

Analysis of frequency spectra of electromagnetic waves emitted by GSM antennas located in the proximity of apiaries STP 1, STP 2, and STP 3 (500 m)

In this analysis, the frequency spectra recorded at three locations (VN, IL, and AG), with apiaries about 500 m from the measurement point, were compared. In VN and IL, signals appeared within ANCOM-licensed mobile communication bands-around 1745 MHz (GSM 1800 / LTE Band 3) and 896 MHz (GSM 900)-confirming active, legal use of 2G–4G frequencies. However, additional peaks may indicate industrial emissions or unauthorized interference. These results reveal spatial variability in electromagnetic exposure near apiaries and form a basis for evaluating possible effects on honeybee colony health.

Monitoring the health status of honey bee colonies at STP 1 – VN (2023–2025); analysis of the impact of non-ionizing electromagnetic radiation on colony health

Between 2023 and 2025, the private VN apiary, located near non-ionizing electromagnetic radiation sources (0–500 m), was monitored to assess possible biological effects on honeybee colony health (Table 3).

Table 3

Seasonal evolution of honey bee colony health at STP 1 – VN (2023–2025)

Location – STP 1 (VN)	2023 Inactive season (Sept.–Mar.)	2024Active season (Apr.–Aug.)	2025 Active season (Apr.–Sept.)
Number of bee colonies	40	45	35
Laboratory diagnosis	suspected European foulbrood and intoxication	nosemosis	suspected intoxication

The results show a progressive decline in the physiological and behavioral condition of bee colonies, accompanied by a reduction in colony number from 40 to 35. In 2023, clinical signs consistent with European foulbrood and possible intoxication were noted-extended proboscis, convulsions, wing deformities, and cuticle or brood alterations. In 2024, symptoms characteristic of nosemosis predominated, including abdominal distension, yellow-green diarrhea, sour hive odor, and reduced foraging (Figure 3**)**.

By 2025, clinical findings indicated severe intoxication or pronounced neurotoxic stress, manifested through agitation, paralysis, increased mortality at hive entrances, and malformed nymphs.

(a) (b) (c)

Fig. 3 - Suspected European foulbrood (a), nosemosis (b), and intoxication (c)

The behavioral disturbances recorded over the three beekeeping seasons-including partial depopulation and disorganized flight-raise concerns about the cumulative influence of environmental factors, with direct effects on the vitality and functioning of honeybee colonies (Table 4).

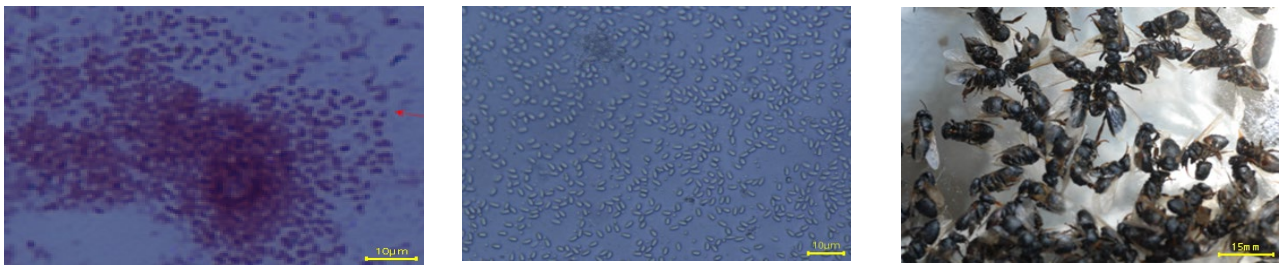
Table 4

Physiological status, activity, and clinical signs of honey bee colonies in STP 1–VN (Experimental lot, 2023–2025)

Laboratory diagnosis / Clinical signs / Beekeeping years			Common signs (2023–2025)
2023	2024	2025	
extended proboscis (extruded mouthparts)	extended proboscis	bees unable to fly, in agony	behavioral changes during foraging
bees crawling and jumping on the ground	pasty yellow-green diarrhea	bees unable to fly, showing signs of agony	reduced flight activity
deformed/twisted wings, successive convulsions	sour odor in the hive	tremors of antennae, wings, and legs	agitation
disoriented flight, rotational movements, grooming behavior	partial depopulation (reduced foragers)	altered leg position, stinger protrusion	worker bee survival rate of up to 30 days
darkened cuticle coloration	reduced foraging activity	uncoordinated movements	progressive mortality
brood discoloration (grey-yellowish)		paresis and paralysis of wings and legs	
combs with altered larval position		death on the hive entrance board (young and adult bees)	
pupae–adult stage unable to emerge		abnormalities in pupae and emerged bees, larvae/nymphs discarded in front of hive entrance	

Laboratory tests confirmed the field clinical suspicions, revealing major pathological changes in the analyzed colonies. Morphoclinical and microbiological examinations identified *Melissococcus plutonius*, the etiological agent of European foulbrood, a severe bacterial disease affecting larvae and brood development. A massive *Nosema spp*. infestation was also detected, indicating advanced nosemosis that weakens adult bees, shortens lifespan, and impairs orientation (Figure 4**)**.

Additionally, correlated clinical and laboratory data supported a diagnosis of exogenous intoxication (phytosanitary or alimentary), evidenced by numerous dead bees showing neurological and motor disorders. The results outline a clear pattern linking these disorders to environmental exposure factors.



(a) (b) (c)

Fig. 4 - Clinical signs observed in honey bee colonies: (a) European foulbrood, (b) nosemosis, (c) intoxication.

In the VN county location, power density measurements within 0–500 m of the GSM source showed notable variations, with a maximum at 10 m (37.99 mW/m²) and secondary peaks at 400 m (6.43 mW/m²), likely due to signal reflections and local topography. Spectrum analysis confirmed 1800 MHz emissions licensed by ANCOM for 2G/4G services, indicating regulatory compliance.

However, monitoring from 2023–2025 revealed progressive colony decline-reduced population, clinical signs of intoxication and parasitic disease, and increased mortality. Correlation of data indicates that, although EMF values were within legal limits, chronic exposure combined with biological and toxic stressors may contribute to physiological imbalance and weakened immunity in honeybee colonies, predisposing them to pathogenic infections.

Monitoring the health status of honey bee colonies at STP 2 – IL (2023–2025); analysis of the impact of non-ionizing electromagnetic radiation on colony health

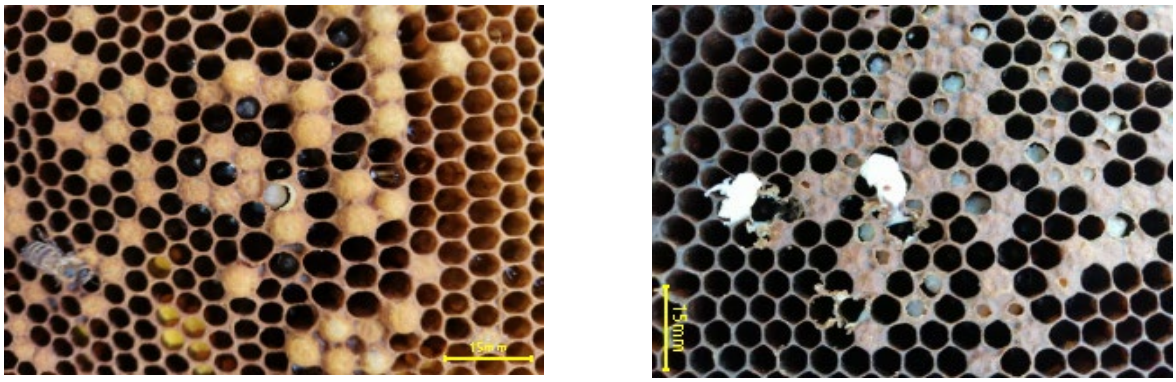
Between 2023 and 2025, the private apiary in IL county, situated near non-ionizing electromagnetic radiation sources, was included in the experimental monitoring program. During this period, colony numbers declined sharply—from 19 in 2023 to 12 in 2025—indicating a clear trend of progressive depopulation in the monitored honeybee colonies (Table 5).

Tabel 5

Seasonal evolution of honey bee colony health at STP 2 – IL (2023–2025, Experimental lot)

Location – STP 2 (IL)	Inactive season 2023 (Sept.–Mar.)	Active season 2024 (Apr.–Aug.)	Active season 2025 (Apr.–Sept.)
Number of bee colonies	19	11	12
Laboratory diagnosis	nosemosis; chalkbrood	chalkbrood	nosemosis; chalkbrood

The clinical signs observed included brood alterations (whitish-gray discoloration, incomplete emergence), bees with enlarged abdomens, pasty diarrhea, acidic odor in the hive, and reduced flight and foraging activity. In addition, partial hive abandonment and abnormal foraging behavior, manifested by agitation and disorientation, were also noted (Figure 5.).



(a) (b)

Fig. 5 - Diagnosis of mixed disease (varroosis + chalkbrood/stonebrood) at STP 2 (IL)

In the IL county location (STP 2), power density showed uneven distribution, peaking at 400 m (39.05 mW/m²), likely due to signal reflections. Colonies displayed agitation and reduced flight activity, suggesting chronic physiological and immunological stress that impaired brood development and adult bee condition. Elevated mortality and abnormal behavior support the hypothesis that persistent environmental stressors, combined with electromagnetic field exposure, negatively affect colony health, viability, and regeneration (Table 6).

Table 6

Evaluation of the physiological condition, colony activity, and clinical signs recorded in the monitoring sheet for STP 2-IL during the 2023–2025 beekeeping seasons (Experimental lot)

Laboratory diagnosis / Clinical signs of disease / Active beekeeping years			Common Clinical Signs 2023–2024–2025
2023	2024	2025	
combs with larval alterations, brood discoloration (white-gray),	combs showing larval alterations, brood discoloration (white-gray)	combs with larval alterations, brood discoloration (white–gray)	behavioral changes of bees during foraging
brood in the pupal–adult stage unable to emerge	brood in pupal–adult stage unable to emerge	brood in pupal–adult stage unable to emerge	partial depopulation through a reduction in the number of forager bees
bees with enlarged abdomens	reduced foraging activity	bees with enlarged abdomens	30-day survival rate of worker bees
diarrhea with a pasty consistency (yellow-green)		diarrhea with pasty consistency (yellow–green)	agitation
emission of an acidic odor from the hive		emission of sour odor from the hive	progressive mortality
partial abandonment of		partial abandonment of	

Laboratory diagnosis / Clinical signs of disease / Active beekeeping years			Common Clinical Signs 2023–2024–2025
2023	2024	2025	
the hive by bees		the hive by bees	
reduced foraging activity		reduced foraging activity	

Laboratory analyses confirmed the simultaneous presence of two major diseases—nosemosis and chalkbrood—in the monitored colonies. Both were detected throughout the study, with clinical signs intensifying during active seasons. Nosemosis, caused by Nosema spp., was verified microscopically by the high spore load in samples from periods of intense colony activity, correlating with physiological stress, high temperatures, and nutritional imbalance. Chalkbrood, produced by Ascosphaera apis, was identified through dead larvae with whitish fungal mycelium inside brood cells.

In the IL location, measurements revealed an unusual pattern: the highest electromagnetic power densities occurred not directly under the antenna, but at 300–500 m, where mean levels reached 31.70–39.05 mW/m² and peaks up to 45.98 mW/m². This atypical distribution, caused by secondary lobes and signal reflections, challenges the assumption that distance alone ensures protection and underscores the need for on-site exposure assessments before establishing apiaries.

Spectrum analysis confirmed GSM 900 MHz emissions compliant with ANCOM allocations, indicating stable local radiation sources. Correlated with colony monitoring, a steady decline was noted—from 19 colonies in 2023 to 12 in 2025—alongside brood anomalies, diarrhea, reduced foraging, and high mortality. The alignment between persistent field intensity and declining colony health supports the hypothesis that EMF exposure, combined with biological and toxic stressors, increases honeybee vulnerability.

Monitoring the health status of honeybee colonies at STP 3–AG (2023–2025); analysis of the impact of non-ionizing electromagnetic radiation on colony health

Within the 2023–2025 monitoring period, the private apiary 3 (AG) maintained a stable population of 85 colonies and was clinically classified as healthy during both active and inactive seasons (Table 7). However, field observations consistently noted behavioral anomalies during foraging—agitation and increased aggressiveness—recurring in all three seasons (Table 8). Consequently, this apiary was designated as the control group for the study.

Table 7

Evolution of colony population and clinical diagnosis for apiary STP 3 – AG (2023–2025) (Control lot)

Location – STP 3 (AG)	Active beekeeping years			
	2023	2024	2025	2025
	Inactive season (Sept.–Mar.)	Active season (Apr.–Aug.)	Inactive season (Sept.–Mar.)	Active season (Apr.–Sept.)
Number of bee colonies	85	85	85	85
Laboratory diagnosis	clinically healthy			

Table 8

Laboratory diagnosis and clinical signs observed in the active beekeeping years 2023–2025

Laboratory diagnosis / Active beekeeping years 2023–2024–2025 / Clinical disease signs	Common Clinical Signs Observed in 2023–2025
clinically healthy	behavioral changes of bees during foraging (agitated, aggressive)
	decrease in pollen-collecting activity
	worker bee survival rate of up to 30 days
	agitated and aggressive bees

Although no evident pathologies or physiological impairments were observed in brood or adult bees, the recorded behavioral deviations suggest moderate environmental stress possibly linked to local factors not reflected in standard diagnostics. In AG, field intensity peaked beneath the antenna (~10 mW/m²) and decreased uniformly to ~0.30 mW/m² at 500 m, confirming an environment with minimal reflections and safe exposure levels beyond 200–300 m. Biologically, the apiary maintained a stable population of 85 colonies during 2023–2025, remaining clinically healthy. However, recurring agitation,

aggressiveness, and reduced pollen collection during foraging indicate subtle behavioral effects of chronic electromagnetic exposure, even in the absence of overt disease.

Comparative analysis of the health status of honeybee colonies from three apiaries (VN STP 1, IL STP 2, and AG STP 3) exposed to non-ionizing electromagnetic radiation (0–500 m)

The comparative analysis of the three apiaries monitored during 2023–2025, located in the proximity of non-ionizing electromagnetic radiation sources (0–500 m), highlights notable differences regarding the health status and stability of honeybee colonies (Table 9).

Table 9

Honeybee colony dynamics in experimental private apiaries (Inactive and Active Seasons, 2023–2025)

Location	Number of Honeybee Colonies			
	2023 Inactive season (Sept.–Mar.)	2024 Active season (Apr.–Aug.)	2025 Inactive season (Sept.–Mar.)	2025 Active season (Apr.–Sept.)
VN STP 1	40	45	29	35
IL STP 2	19	11	18	12
AG STP 3	85	85	85	85

The VN apiary (STP 1) showed a moderate colony decline from 40 to 35 and recurrent disease signs—intoxication, European foulbrood, and nosemosis—with pronounced neurological and physiological symptoms. The IL apiary (STP 2) experienced significant depopulation from 19 to 12 colonies, consistently affected by nosemosis and chalkbrood, indicating immunological stress and brood deterioration. The AG apiary (STP 3) maintained 85 healthy colonies throughout 2023–2025, serving as the control group. However, persistent agitation and aggressiveness during foraging suggested moderate stress linked to electromagnetic emissions from the GSM source.

The comparative analysis of the three locations (VN, IL, and AG) revealed marked differences in electromagnetic field distribution and colony evolution. In VN, peaks occurred at 10 m (37.99 mW/m²) and 400 m (6.43 mW/m²), with signals in the GSM 1800 band (1710–1785 MHz) compliant with ANCOM regulations. Colony numbers declined from 40 to 35, with severe symptoms—nosemosis, intoxication, and high mortality. In IL, maximum exposure appeared at 300–400 m (31.70–39.05 mW/m², peaks 41.87–45.98 mW/m²), exceeding near-field levels (3–9 mW/m²). The GSM 900 (896.82 MHz) signal was authorized, yet the apiary showed progressive depopulation (19 → 12 colonies) and persistent disease signs—brood damage, diarrhea, and mortality. In AG, field intensity decreased uniformly from 10.3 mW/m² beneath the antenna to 0.30 mW/m² at 500 m, with no major reflections. Colonies remained constant (85) and clinically healthy, though behavioral stress—agitation, aggressiveness, reduced foraging—was recurrent.

Overall, non-uniform EM field distribution (VN, IL) correlated with colony decline and pathology, whereas predictable, attenuated exposure (AG) did not cause depopulation but induced moderate behavioral stress.

The study revealed clear differences between locations: in VN and IL, where electromagnetic field distribution showed irregular peaks, colonies underwent progressive depopulation and higher mortality. In contrast, in AG, where field propagation decreased uniformly and exposure levels were lower, colonies remained clinically healthy but displayed recurrent behavioral anomalies. These findings align with previous research—experimental studies (*Westerdahl & Gary, 1981b; Harst et al., 2006; Kumar & Sangwan, 2011*) reported similar behavioral disruptions, reduced lifespan, and colony density. Recent analyses (*Balmori, 2021; Vilić et al., 2024; Szychta et al., 2024*) also suggest that chronic EMF exposure triggers oxidative stress and increased disease susceptibility, explaining the observed progressive symptoms. Moreover, literature highlights the multifactorial nature of pollinator decline (*Ratnieks et al., 2010; Cucurachi et al., 2013*), where EMF acts synergistically with other environmental stressors.

Statistical analysis of honeybee colony dynamics under electromagnetic field exposure

Statistical analysis showed that colony numbers across the four activity periods generally followed a normal distribution, except in AG STP 3, where the population remained stable. The Shapiro–Wilk test (n = 3–50) gave W values near 1 for VN STP 1 (0.9940) and IL STP 2 (0.8440), confirming

data normality and enabling valid comparisons with the control group (Table 10). ANOVA followed by Dunnett's test revealed highly significant differences ($p < 0.0001$) between the control (AG STP 3) and experimental sites, with mean differences of 47.75 colonies versus VN STP 1 and 70 versus IL STP 2. The coefficient of variation supported these findings, at 18.39% (VN) and 27.22% (IL), indicating higher colony number variability.

Table 10

One-way ANOVA followed by Dunnett's multiple comparisons test

Number of families	1				
Number of comparisons per family	2				
Alpha	0.05				
Dunnett's multiple comparisons test	Mean Diff.	95.00% CI of diff.	Below threshold?	Summary	Adjusted P Value
AG STP 3 vs. VN STP 1	47.75	39.24 to 56.26	Yes	****	<0.0001
AG STP 3 vs. IL STP 2	70.00	61.49 to 78.51	Yes	****	<0.0001
Test details	Mean 1	Mean 2	Mean Diff.	SE of diff.	n1
AG STP 3 vs. VN STP 1	85.00	37.25	47.75	3.255	4
AG STP 3 vs. IL STP 2	85.00	15.00	70.00	3.255	4

Correlation analysis between electromagnetic field intensity and colony dynamics showed a strong negative relationship in VN STP 1, where rising EMF levels coincided with colony decline, and a positive relationship in IL STP 2, likely due to the natural selection of more resilient colonies over four beekeeping cycles. In AG STP 3, no correlation was observed because colony numbers remained constant (Table 11).

Table 11

Calculated correlation coefficients (Pearson and Spearman)

Apiary	Pearson r	p(Pearson)	Spearman rho	p(Spearman)
VN STP 1	-1.0	1.0	-1.0	-
IL STP 2	1.0	1.0	1.0	-
AG STP 3	0.0	1.0	-	-

Practical Recommendations for Beekeepers

To reduce risks from electromagnetic field exposure, apiaries should not be placed near antennas or other strong radiation sources, and exposure levels should be periodically measured with portable instruments. Distributing colonies across multiple sites helps minimize risk and enables comparative monitoring. Continuous observation of bee behavior—especially agitation and foraging activity—facilitates early detection of stress. Adequate nutrition and strict disease control further enhance colony resilience. Cooperation between beekeepers and authorities, along with prompt reporting of abnormal mortality, can improve EMF monitoring and support long-term honeybee health protection.

CONCLUSIONS

Exposure to intense or reflected electromagnetic fields can adversely affect honeybee colonies, leading to agitation, disorientation, reduced foraging, and increased mortality. These findings emphasize the need to monitor EMF levels in beekeeping areas. Differences between apiaries demonstrate variable colony responses to local conditions, where EMF may act synergistically with other stressors to impair health. Such exposure can trigger physiological imbalances and oxidative stress, weakening immunity and reducing colony resilience. Consequently, behavioral changes during foraging—agitation, fewer foragers, and shortened worker lifespan (≈30 days)—were associated with progressive depopulation and colony mortality.

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DETERMINATION OF THE OBJECTIVE FUNCTION REGARDING THE CORRELATION BETWEEN THE TRAVEL SPEED AND THE WORKING SPEED OF THE MOWER, WITH APPLICATION ON THE BCS 740 MOTOR-CULTIVATOR TO OPTIMIZE THE WORKING SPEED

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DETERMINAREA FUNCȚIEI-OBIECTIV PRIVIND CORELAREA VITEZEI DE DEPLASARE ȘI A VITEZEI DE LUCRU A COSITOAREI, CU APLICAREA PE MOTOCULTORUL BCS 740 PENTRU OPTIMIZAREA VITEZEI DE LUCRU

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ABSTRACT
This article presents the determination of an objective function that aims to correlate the travel speed of the tiller and the working speed of the reciprocating mower, in order to maximize productivity and minimize losses caused by overlap or gaps between cuts. The determined objective function allows the estimation of the optimal working speed, adjusted by safety and penalty coefficients (k and λ), and we used it in determining the working speed and the tiller for the BCS 740 tiller equipment. The results of the calculations using the technical characteristics of the BCS 740 tiller show that choosing the gear as close as possible to Vopt minimizes productivity losses and energy consumption.

REZUMAT
Acest articol prezintă determinarea unei funcții-obiectiv prin care se urmareste corelarea vitezei de deplasare a motocultorului și vitezei de lucru a cositoarei alternative, cu scopul de a maximiza productivitatea și a minimiza pierderile cauzate de suprapunerea sau golurile între tăieturi. Funcția-obiectiv determinata permite estimarea vitezei optime de lucru, ajustată prin coeficienți de siguranță și penalizare (k și λ), și am utilizat-o in determinarea vitezei de lucru si a motocultorului pentru echipamentul motocultor BCS 740. Rezultatele in urma calculelor folosind caracteristicile tehnice ale motocultorului BCS 740 arată că alegerea treptei de viteză cât mai apropiate de V_{opt} *minimizează pierderile de productivitate și consumul de energie.*

1. INTRODUCTION

The use of motorized tillers is essential for small and medium-sized farms (up to 4 ha), as motorized tillers represent an affordable solution for mechanized agricultural work. According to a study, approximately 43% of Romania's agricultural area is located on sloping land *(wikipedia.org)*. Considering that Romania's total agricultural area is approximately 13.5 million hectares, approximately 5.8 million hectares are sloping agricultural land *(https://iuls.ro/universitate/despre-universitate*). Furthermore, data show that 48% of Romania's total agricultural area is represented by permanent grassland, indicating a significant proportion of agricultural land located on slopes *(https://www.pajisti-grassland.ro/)*. These data highlight the importance of proper management of sloping land to prevent soil degradation and ensure sustainable agriculture *(Biris et al., 2024)* Of these, 1.524 million hectares are hayfields, mainly used for hay production.

A critical aspect in the operation of motorized tillers is the correlation between the speed of the tiller and the working speed of the equipment carried and driven from the power take-off of the tiller *(Ahmad, et al., 2015)*.

One of the cases is the mowing operation in which the technological process depends mainly on two factors, namely the speed of the tiller and the working speed of the mower *(Buzea, 1988)*.

The speed of the tiller also depends on the technical characteristics of the kinematic chain, the gearbox and the characteristics of the running system with which the tiller is equipped (diameter of tires or metal wheels). The working speed of the mower also depends on the technical characteristics of the

kinematic chain, the speed of the tiller's power take-off and the characteristics of the kinematic chain through which the circular motion is transformed into rectilinear motion. The present material aims to present the determination of an objective function that aims to correlate the speed of the motor-cultivator and the working speed of the alternative mower and its use in determining the working speed of the mower and the speed of the motor-cultivator for the BCS 740 motor-cultivator equipment using the technical characteristics of the motor-cultivator. The specialized literature indicates that the optimization of this ratio can be mathematically formulated through an objective function, which penalizes deviations from the optimal regime *(Mocanu, 1997).* The productivity of alternative mowers critically depends on the speed of the motor-cultivator and the frequency of the blades. Too high an advance can leave uncut areas, and excessive overlap generates energy losses and additional wear. Choosing an optimal advance speed is an important issue of agricultural mechanization, with a direct impact on energy efficiency and work quality.

These issues have been addressed in the papers: *(Tomescu et al., 1985; Buzea, 1988; Mocanu, 1997; Biris and Drenea, 2025; Biris et al., 2024; Biris and Drenea, 2025; Popovici et al., 2018; Sharma et al., 2016; Kepner et al., 1982; Ahmad et al., 2015; wikipedia.org; https://iuls.ro/universitate/despre-universitate/; https://www.pajisti-grassland.ro/; https://madr.ro/; Technical data of the motor cultivator (mass 112 kg, engine 12 HP).*

2. MATERIALS AND METHODS

The process of mowing grass is carried out by cutting the stems of plants. For the mechanical separation of the parts of the plant stem, not only the cutting method can be used, but also other methods such as, for example, breaking by bending the stem and cutting by shearing. The most suitable method is by shearing. At the moment, there are three types of cutting devices, namely normal cutting, low cutting and medium cutting. Parameters that characterize the type of a cutting device refer to the dimensions of the cutting part and the counter-cutting part as well as the value of the knife stroke. The essential technical characteristics of a mower are: t - the pitch of the cutting blades, the value of which is determined by the size of the base of the cutting blade; t_o the pitch of the fingers, which represents the distance between the median lines of the fingers and S - the knife stroke. Depending on these technical characteristics, the technological process of mowing is classified as follows

In the cutting device, the cutting part is presented by the cutting blade edge which is a movable element and the fingers represent the counter-cutting part which with the help of its lateral edges maintain the stem subjected to cutting thus due to the alternative back and forth movement of the knife the cutting speed of the blade changes from zero at the dead point to a maximum because at the middle of the knife stroke therefore it is natural to expect that near this position there is the possibility of cutting the stems by the knife without the counter-cutting part. In this case, for cutting without the counter-cutting part, such a knife speed is necessary which far exceeds the speeds that exist in reality in existing equipment In this case the speed should be from 3 m/s to 5 m/s but in reality the speed does not exceed 3 m/s. So the importance is the speed of the mower knife on the quality of cutting but it must also be linked to the speed of movement of the machine itself. Experience and studies show that the ratio between the knife speed and the machine's forward speed. These cannot be chosen arbitrarily but must have an optimally determined value. From the specialized literature, the average knife speed that ensures the optimal technological effect is given by the relationship

Where

$$V_{mc} = \beta V_m \text{ [m/s]} \quad (1)$$

V_{mc} average speed of the blade

V_m speed of the motor cultivator

β– coefficient that depends on the mode of operation of the mower and has values between 1.25 – 1.30

If we consider the average speed of the blade which is determined by the relation

$$V_{mc} = \frac{S}{30} n \text{ [m/s]} \quad (2)$$

where

S - knife stroke

n - speed at the drive shaft of the mower mechanism

And the speed of the tiller is given by

$$V_m = \frac{hn}{30} \text{ [m/s]} \quad (3)$$

Where h is the power of the tiller per stroke of the knife and n is the rotation of the crank, then the result is

$$\beta = \frac{v_{mc}}{v_m} = \frac{S}{h} \quad (4)$$

$$S = \beta h \quad (5)$$

Therefore, small values of β correspond to large values of h and vice versa. From what is presented above, it follows that the power supply for mowers depends on the coefficient β which is not determined by calculations but by means of experiments and its value is in the range 1.25 - 1.30.

2.1 Determination of an objective function regarding the correlation between the travel speed and the working speed of the mower.

Having the initial data respectively:

V_m = speed of the tiller [m/s]

f = frequency of the blade [Hz]

t = pitch of the blade section [m] it can be 76.2 mm and 152.4 mm (*Biris and Drenea, 2025).*

L = working width [m]

First of all, we determined the race lead with the formula

$$a = \frac{V_m}{f} \text{ [m/ double race]} \quad (6)$$

Where a represents the distance traveled by the tiller (forward) during one complete movement of the mower blade (one stroke).

Explanation

In a reciprocating mower, the blade moves back and forth with a certain frequency (f, strokes per second).

The tiller moves forward with a speed V_m [m/s]

In one second, the tiller moves forward with V_m [m/s].

In the same second, the blade makes f strokes.

The stroke advance is important because the stroke advance (a) is greater than the pitch of the blade section (t) → uncut gaps remain. If the stroke advance is much smaller than the pitch → overlap occurs and energy is lost. The ideal condition would be that: a ≈ t, i.e. the stroke advance is equal to the length of the blade pitch → complete and efficient cutting.

Considering that the mowing technological process is not carried out under ideal conditions, we established a penalty function for the section advance/step deviation:

$$E(V) = (a - t)^2 = (\frac{v_m}{f} - t)^2 \quad (6)$$

We arrived at this penalty function as follows: starting from the fact that the goal is to have the feed per stroke (*a*) as close as possible to the pitch of the knife section (t). In this case, if $a=t$ the mower cuts completely, without gaps and without overlaps, or if $a \neq t$ a deviation occurs that leads to losses. So the difference between a and t must be established. This deviation is expressed by the formula:

$$\Delta = a - t \quad (7)$$

This difference can be positive (too much lead → gaps) or negative (too little lead → overlap). But for losses, it is not the sign that matters, but how big the difference is.

That is why the square is taken:

$$E(V) = (a - t)^2 \quad (8)$$

This is the penalty function – the more the feedrate differs from the step, the more the loss increases.

Why is it quadratic (and not absolute or something else)?

- Because the penalty increases rapidly with the deviation → even a small difference becomes significant.
- The square is symmetric (it penalizes both too small and too large feedrates).
- Mathematically, a quadratic function is easier to integrate into optimization models and allows the use of analytical methods.

Having thus defined some of the terms, we established the effective productivity function:

$$J(V_m) = V_m L \exp[-\lambda (\frac{v_m}{f} - t)^2] \quad (9)$$

where it results that the effective productivity (J(V_m)) of a mower depends on: the speed of travel V_m [m/s] → the higher the speed of travel of the tiller, the larger the mowed area and the working width L [m] → the blade covers a strip of grass of this width. If everything were perfect (without losses), productivity would be simple:

$$J_{ideal} = V_m L \quad (10)$$

where it results (area cut per second).

But in reality, if the feed rate per stroke (a=V_m /f) is not equal to the section pitch (t), losses occur:

a > t → uncut gaps remain.

a < t → overlap occurs and time/energy is lost.

Considering the above, it results that the function regarding productivity. So productivity must be corrected with a function that decreases when (a−t) increases.

Choosing the multiplicative penalty function

For this, a function of the type:

$$P(V_m) = \exp[-\lambda (\frac{v_m}{f} - t)^2] \quad (11)$$

Where $(\frac{v_m}{f} - t)^2$= squared deviation (symmetric, increases rapidly with the difference) and λ - coefficient that regulates the severity of the penalty. The exponential function has the advantage that when a = t we have P(V_m) = 1 (i.e. without losses) and in the case of a-t increases, P(V_m) = 1 decreases rapidly towards 0.

Considering the above, we have combined the ideal productivity formula with the penalty expression, resulting in the effective productivity formula below:

$$J\left(V_m\right) = V_m L \exp[-\lambda (\frac{v_m}{f} - t)^2] \quad (12)$$

Thus having V_m L = ideal productivity.

Exponential term = efficiency factor (between 0 and 1)

J (V_m) = effective (realistic) productivity ensures:

Direct connection of mechanical movement (advance/step) to agricultural productivity.

It has a clear maximum → exactly at the optimal speed where $a \approx t$

It can be used in analytical or numerical optimization.

At the same time, the formula is a combination of: theoretical productivity and exponential penalty for deviations from the ideal regime.

The coefficient λ controls how severely we penalize deviations between the feed rate per stroke (V/f) and the section pitch t *(Popovici et al., 2018; Singh et al., 2017)* λ does not come from a direct formula, but from experimentation and calibration

Thus if λ is large → even a small difference leads to large decreases in productivity (very sensitive system, strict cutting) or if λ is small → even large differences are tolerated, and the penalty remains low

Thus λ is taken from the specialized literature and has values in the range $5 \leq \lambda \leq 20$.

λ ≈ 5 → moderate penalty, for mowers used on relatively uniform terrain.

λ ≈ 10 → medium penalty, balance between theory and practice.

λ > 15 → very strict, recommended only for precision work or laboratory testing.

Thus the value of λ is calibrated experimentally for each machine and type of terrain. In applied work, λ ≈ 10 is most often used, which ensures a realistic compromise

Expression of the optimal working speed:

$$V_{opt} = k\,f\,t \tag{13}$$

The k coefficient has the following role and sources:

k – safety factor: adjusts the theoretical maximum speed to avoid gaps between cuts, taking into account the variability of the terrain, unevenness, tire slip and small variations in PTO speed. The literature recommends values between 0.8 and 0.9. The choice of k = 0.85 represents a balanced compromise between productivity and safety *(Biris et al., 2024; Biris and Drenea, 2025).*

Having thus established the expression of the objective function, we proceeded to apply it for a specific case considering the BCS 740 Motocultor equipment.

This equipment has the following parameters applied as follows:

Working width of the mower: L = 1.15 m

Blade section pitch: t = 0.0762 m

Safety factor: k = 0.85

Penalty coefficient: λ = 10

Available speed ranges: Gear I = 2.0 km/h, Gear II = 2.92 km/h, Gear III = 4.3 km/h

Blade frequencies: f = 1000 spm (16.667 Hz) and f = 1600 spm (26.667 Hz)

However, the objective function also has a series of restrictive conditions (typical for BCS 740 + mower) as follows:

Constructive limitations of the speed of the tiller: the speeds of the tiller $V_m \in (V_1\ V_2 V_3)$

Constructive limitations of the frequency blade: $f \in (f_1\ f_2)$ — depending on the engine PTO mode.

Kinematic compatibility for complete cutting: V<f t k (travel speed cannot exceed the optimal feed speed per stroke).

RESULTS

Considering the technical characteristics of the BCS 740 motor-cultivator and the working frequency of the mower blade, the optimal speed was determined, obtaining the following results:

Relevant "theoretical" speeds

Ideal speed (without safety factor) — here $E(V) = 0$ (i.e. V/f = t) appears

$$V_{ideal} = f\,t$$

for $f_1 = 1000\ spm$ $V_{ideal\,1} = 1,27\ m/s$ =4,572 km /h

for $f_2 = 1600\ spm$ $V_{ideal\,2} = 2,032\ m/s$ =7,315 km /h

Recommended speed applying the safety factor k (practical recommendation to avoid gaps):

$$V_{opt} = k\,f\,t$$

for f_1 $V_{opt\,1} = 1,0795\ m/s$ = 3,886 km /h

for f_2 $V_{opt\,2} = 1,7272\ m/s$ = 6,218 km /h Note:

$V_{ideal\,1} > V_{opt\,1}$ $V_{ideal\,2} > V_{opt\,2}$

because k<1 — i.e. the speed that theoretically maximizes J is $V = f\ t$, but we suggest $k\ f\ t$ as it is at the practical limit.

Applying the effective productivity function

$$J\ (V_m) = V_m\ L\ \exp[\ -\lambda\ (\frac{v_m}{f} - t)^2]$$

We calculated $J\ (V_m)$ for each BCS 740 stage and for the "optimal" and "ideal" speeds. And we arrived at the results in table no. 1 and table no. 2

Table 1

Optimal working speeds of the BCS 740 motor-cultivator for a number of knife strokes of 1000 strokes/minute

Tip / V (km/h)	V (m/s)	J pentru f=1000 spm (m²/s)	% față de $J_{ideal\,1}$
Treapta I (2,00 km/h)	0,5556	0.627	42.95%
Treapta II (2,92 km/h)	0,8111	0.926	63.38%
Treapta III (4,30 km/h)	1,1944	1.373	94.03%
$V_{opt\,1}$	1,0795	1.240	84.82% (față de ideal: 84.82%)
$V_{ideal\,1}$	1,2700	1.461	(100%) — maxim teoretic

Table 2

Optimal working speeds of the BCS 740 motor-cultivator for a number of knife strokes of 1600 strokes/minute

Tip / V (km/h)	V (m/s)	J pentru f=1600 spm (m²/s)	% fata de $J_{ideal\,2}$
Treapta I (2,00 km/h)	0,5556	0.620	26.51%
Treapta II (2,92 km/h)	0,8111	0.913	39.09%
Treapta III (4,30 km/h)	1,1944	1.360	58.20%
$V_{opt\,2}$	1,7272	1.984	84.91%
$V_{ideal\,2}$	2,0320	2.337	(100%) — maxim teoretic

Practical interpretation — what the numbers mean

• For f = 1000 spm (16.667 Hz, s = 76.2 mm):

Gear III (4.30 km/h) provides ~94% of the theoretical maximum productivity (very close to ideal).

Gear II (2.92 km/h) provides ~63% of the ideal.

$V_{opt\,1}$ = 3.886 km/h (recommended with k = 0.85) is a good choice if you want more safety; it gives ~85% of the ideal.

For f = 1600 spm (26.667 Hz):

The ideal speed is ~7.32 km/h — it exceeds the capacity of the BCS 740 (maximum gear 4.30 km/h).

Thus, even gear III only achieves ~58% of the ideal theoretical productivity at this frequency.

If you use 1600 spm, to get closer to the ideal you need either a faster tiller, or a smaller *t* pitch (more frequent knives), or to accept overlap (i.e. loss of productivity at the available speed).

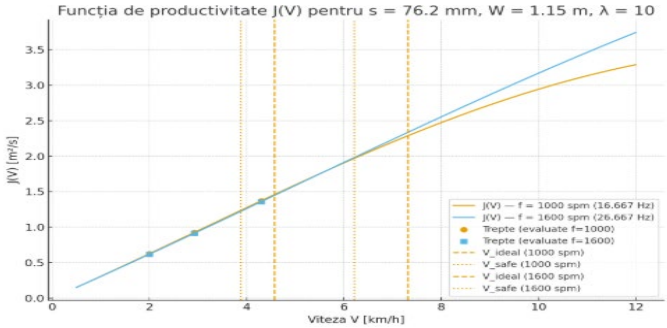

Fig. 1 - Graphical presentation of the productivity function as a function of the speeds of the BCS 740 tiller

We generated a graph with the available Speed steps vs V_{opt} for the two working frequencies of the mower (1000 and 1600 spm).

Here is how it could look visually:

On the X axis: the available speed steps (Stage I, II, III).

On the Y axis: the speed in km/h.

Two lines: V_{opt} for f = 1000 spm and V_{opt} for f = 1600 spm.

This graph fig.2 will visually highlight how close the available steps are to the optimal speed.

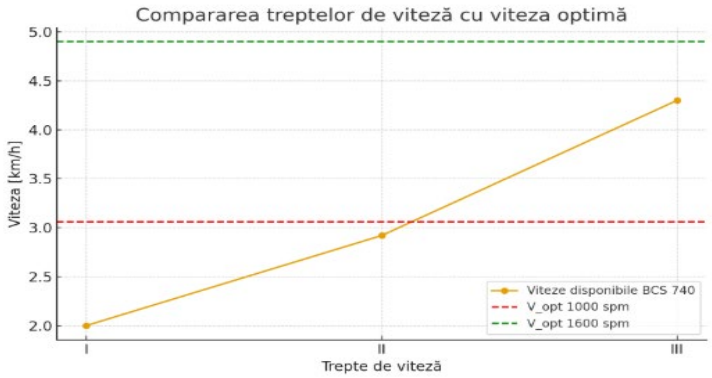

Fig. 2 - Comparison between the available speeds of the BCS 740 motor cultivator with the optimal speeds resulting from the calculations

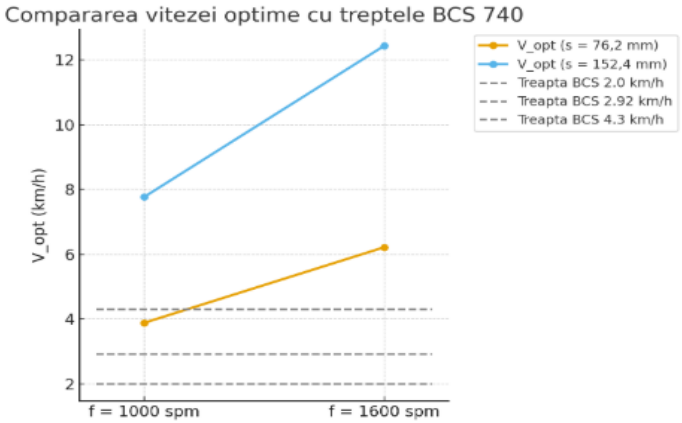

Fig. 3 - Comparison between the available speeds of the BCS 740 motor-cultivator with the optimal speeds resulting from calculations depending on the pitch of the mowing fingers, respectively 76.20 mm and 152.40 mm

CONCLUSIONS

Objective function

$$J\,(V_{m)} = V_m\,L\;\exp[-\lambda\,(\frac{v_m}{f} - t)^2]$$

allows the theoretical correlation between the travel speed of the tiller and the working speed of the mower.

The optimal working speed is

$$\boldsymbol{V}_{\boldsymbol{opt}} = k\;\;f\;t$$

adjusted for real field conditions.

The coefficients *k* = 0.85 and λ = 10 play a critical role: the first adjusts operational safety, and the second penalizes deviations from the section pitch.

The practical application of the model confirms that the II and III gears of the BCS 740 are the closest to the optimal speed for the knife frequencies used. Following the calculations, a series of recommendations can be established regarding the use of the BCS 740 tiller as follows: Using a frequency *f* = 1000 spm and *s* = 76.2 mm → the III gear (4.3 km/h) of the tiller is used even if the optimal speed is , V_{opt} ≈ 3.9 km/h (*k*=0.85). This indicates that the user must make a compromise in the efficient use of the tiller.

Using a frequency *f* = 1600 spm and *s* = 76.2 mm → the BCS 740 tiller cannot reach the ideal speed because the gearbox does not provide a gear ratio necessary for the efficient use of the tiller; recommendations:

o reduce the mower's working frequency to ~1000 spm (if possible) or

o use a smaller pitch t (knives with a smaller pitch) or

o accept that you will have sub-ideal overlap / productivity (gear III remains the best option available).

For normal operation: select the BCS gear that gives you the highest *J*. In this case, gear III gives the highest power and the highest J optim but requires f≈ 23.4Hz (≈1404 spm). But considering that the number of strokes of the mower cannot be adjusted to the value of 1404 double strokes per minute, the only solution is to use gear III and a frequency of 1000 double strokes per minute.

If the terrain is uneven, you can redo the calculation using a new value of the coefficient *k* by decreasing the value of 0.8 and redo the calculation, which may result in the third gear of the tiller no longer being the closest to the optimal value.

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THE EVOLUTION OF ROMANIA'S EXPORTS DURING 2020–2024: TRENDS, DESTINATIONS, AND STRUCTURE BY MODES OF TRANSPORT

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EVOLUȚIA EXPORTURILOR ROMÂNIEI ÎN PERIOADA 2020–2024: TENDINȚE, DESTINAȚII ȘI STRUCTURA PE MODURI DE TRANSPORT

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Keywords: *Romania's exports, international trade, transport modes, European Union, trade structure, export competitiveness, trade dynamics*

ABSTRACT

The paper analyzes the evolution of Romania's exports during the period 2020–2024, highlighting the main trends, structures, and dynamics in international trade. Based on official data from the National Institute of Statistics (INS) and supplemented with information from the European Commission, the study provides a quantitative and comparative analysis of exports by transport modes, product categories (according to the Combined Nomenclature), and trading partners both within and outside the European Union. The results reveal a steady upward trend in Romania's export performance, with total FOB exports increasing from €62.1 billion in 2020 to €92.6 billion in 2024. Road transport remains dominant, accounting for over 68% of exports, while maritime and rail transport show moderate but stable growth. Structurally, exports continue to rely heavily on the EU market (over 70%), with Germany, Italy, and France as the main destinations. However, there is a visible diversification towards non-EU markets, particularly Turkey, the Republic of Moldova, and the United States. The study concludes that Romania's foreign trade structure is undergoing a process of consolidation and modernization, supported by improved logistics, expanded regional partnerships, and adaptation to European green trade standards. These transformations indicate a transition from resource-based exports to competitive, value-added, and sustainable international trade.

REZUMAT

Lucrarea analizează evoluția exporturilor României în perioada 2020–2024, evidențiind principalele tendințe, structuri și dinamici din comerțul internațional. Pe baza datelor oficiale furnizate de Institutul Național de Statistică (INS) și completate cu informații din Eurostat și Comisia Europeană, studiul realizează o analiză cantitativă și comparativă a exporturilor în funcție de modurile de transport, grupele de mărfuri (conform Nomenclatorului Combinat) și principalii parteneri comerciali, atât din cadrul, cât și din afara Uniunii Europene. Rezultatele arată o tendință ascendentă constantă a performanței exporturilor României, valoarea totală a exporturilor FOB crescând de la 62,1 miliarde euro în 2020 la 92,6 miliarde euro în 2024. Transportul rutier rămâne predominant (peste 68% din total), în timp ce transportul maritim și feroviar înregistrează o evoluție stabilă. Din punct de vedere structural, exporturile românești se bazează în continuare în proporție majoritară pe piața Uniunii Europene (peste 70%), principalele destinații fiind Germania, Italia și Franța. Totodată, se observă o diversificare semnificativă către piețele non-UE, în special Turcia, Republica Moldova și Statele Unite. Concluziile studiului subliniază faptul că structura comerțului exterior românesc se află într-un proces de consolidare și modernizare, susținut de îmbunătățirea infrastructurii logistice, extinderea parteneriatelor regionale și adaptarea la standardele europene de sustenabilitate. Aceste transformări reflectă tranziția României de la un model economic bazat pe resurse către un comerț internațional competitiv, diversificat și durabil.

INTRODUCTION

In the context of globalization and economic interdependence, international trade represents a fundamental pillar of modern economic development. For Romania, integration into the European Single Market has generated a profound structural transformation of external trade flows, both in terms of volume and geographical and sectoral diversification. Over the past two decades, Romanian exports have become

the main driver of economic growth, contributing significantly to the country's Gross Domestic Product (GDP) and trade balance.

The period **2020–2024** has been particularly complex for the global economy, marked by successive shocks — the COVID-19 pandemic, the energy crisis, supply chain disruptions, and the ongoing armed conflict in Ukraine. These events have significantly influenced the dynamics of international trade, affecting logistics flows, transport costs, and the structure of exports across Europe. In this context, analyzing Romania's export performance provides a clear picture of the adaptability and resilience of the national economy in the face of global structural changes.

The main objective of this study is to evaluate the **evolution of Romania's exports between 2020 and 2024**, through a detailed analysis of:

- FOB export values and the main modes of transportation used;
- product group structures, according to the **Combined Nomenclature (CN)**;
- trade destinations, with emphasis on Romania's relations with the **European Union**; and
- key trends regarding the competitiveness and sustainability of foreign trade.

The analysis is based on official statistical data provided by the **National Institute of Statistics (INS)** and supplemented by thematic European reports (*European Court of Auditors, 2023*). Through a **quantitative and comparative approach**, the study aims to identify the structural dynamics of exports, the main drivers of their growth, and the strategic directions for consolidating Romania's position in the international market.

The relevance of this research lies in providing an **integrated perspective** on the recent transformations in Romania's foreign trade, by correlating economic data with logistic and geopolitical developments. In a European trade environment undergoing accelerated digitalization and a green transition, Romania must redefine its export strategies by increasing value-added production, expanding non-EU partnerships, and optimizing its multimodal transport infrastructure.

MATERIALS AND METHODS

This study is based on a quantitative analysis of Romania's exports during the period 2020–2024, using official data provided by the National Institute of Statistics (INS), available through the TEMPO-Online database and the annual reports on international trade in goods.

The statistical data were collected manually and centralized in a **Microsoft Excel file**, where they were grouped according to the main analytical criteria:

- modes of transport (road, rail, sea, and inland waterways);
- product groups, according to the **Combined Nomenclature (CN)**;
- commercial sections and chapters, distinguishing between total exports and those directed to the European Union;
- and main partner countries (EU and non-EU), based on the INS ranking of the top 50 export destinations.

Data processing was carried out through:

- **comparative temporal analysis (2020–2024)**, to highlight annual trends and variations;
- **calculation of structural and dynamic indicators** (shares, growth rates, and percentage contributions);
- **graphical analysis**, with visual representations created in Excel to illustrate the distribution of exports by product category and destination;
- and **contextual correlation** between trade trends and external economic factors (COVID-19 pandemic, European economic recovery, and the war in Ukraine).

The adopted methodology fits within a **descriptive-comparative analytical framework**, combining basic statistical tools (averages, percentage changes, and dynamic indices) with qualitative economic interpretation. This approach aims to identify structural tendencies and assess the **medium-term competitiveness** of Romania's exports.

RESULTS

This section analyzes the evolution of Romania's exports during the period 2020–2024, based on official data provided by the National Institute of Statistics (INS) and complementary information published by Eurostat.

The main objective is to identify the major trends concerning FOB export values, modes of transport, product group structure, and Romania's main trading destinations within the context of international trade.

During the analyzed period, Romania recorded a **significant increase in export value**, mainly driven by the strengthening of commercial relations with the **European Union (EU)** member states, particularly **Germany, Italy, and France** (*Ilie, 2024*). According to **Eurostat**, **road transport** remained the dominant export channel for Romanian goods, accounting for over **70% of total trade volume** (*Sârbu et al., 2022*).

Amid global economic fluctuations, energy crises, and the reconfiguration of regional logistics chains, the **structure of Romania's exports underwent notable adjustments**, visible both in the **composition of traded goods** and in the **distribution of destination markets** (*Miu and Strâmbovschi, 2025*). At the same time, the process of adaptation to **European sustainability standards** and the new **EU Green Transport Policy** has gradually influenced the logistical and commercial decisions of Romanian exporters (*Busu and Ene, 2025*).

The statistical interpretation in this section aims to highlight:

- the dynamics of export values across the main **modes of transport** (rail, road, maritime, etc.);
- the **share and evolution of key product groups** according to the **Combined Nomenclature (CN)**;
- the **distribution of exports** between **EU Member States** and **third countries**;
- and the general trends regarding the **efficiency and competitiveness** of Romanian exports.

The data used in this analysis come from the official publications of the **National Institute of Statistics (INS)** and **Eurostat** trade reports on the international trade of EU Member States, supplemented by recent academic studies on regional export dynamics (*Tanasiichuk et al., 2025; Hristova-Politikova, 2025*).

1. Evolution of Romania's exports by main modes of transport (2020–2024)

The analysis of exports by main modes of transport reveals **significant changes in the logistical structure** of Romania's international trade. According to data published by the **National Institute of Statistics (INS)**, during **2020–2024**, Romania recorded a **general increase in FOB export value**, from **€62.17 billion in 2020** to **€92.67 billion in 2024**, representing an increase of approximately **49% over five years** (*INS, 2025*).

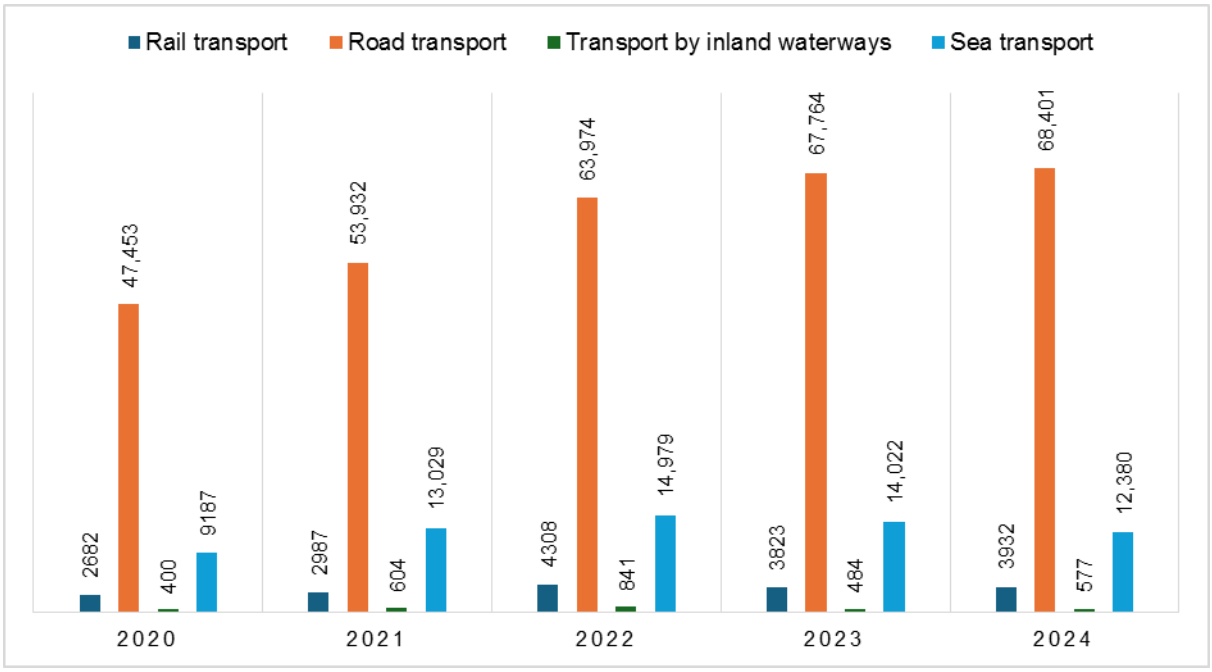

Fig. 1 - Distribution of exports by modes of transport, U.M. = million euros
(NIS, http://statistici.insse.ro)

Road transport continues to hold a dominant share in total exports, with values rising from €47.45 billion in 2020 to €68.40 billion in 2024, representing over 73% of total exports in the last year analyzed. This evolution confirms the role of road infrastructure and automotive transport as the main channel of integration into the European Single Market, particularly due to Romania's geographical proximity and the intensity of trade flows with Germany, Italy, and France (*Ilie, 2024*).

Maritime transport has played an important role, fluctuating between **€9.1 billion (2020)** and a peak of **€14.98 billion in 2022**, followed by a slight decline during **2023–2024**. This trend can be explained by the

dynamics of trade through the **Port of Constanța**, Romania's largest logistical hub on the **Black Sea**, which has been affected by regional disruptions generated by the **conflict in Ukraine** (*Busu and Ene, 2025*).

Rail transport has shown a positive evolution, increasing by **over 46%** during the analyzed period. Although its share in total exports remains modest (below 5%), this growth reflects efforts to **modernize rail infrastructure** and **promote sustainable transport** within the framework of **EU green mobility policies** (*Miu and Strâmbovschi, 2025*).

In contrast, **inland waterway transport** shows a **fluctuating evolution**, reaching a peak of **€841 million in 2022**, followed by a sharp decline in 2023. This trend can be correlated with **low water levels on the Danube River** and seasonal **logistical restrictions on navigability** (*Hristova-Politikova, 2025*).

General Trends (2020–2024)

1. The **dominance of road transport** in the export structure, supported by the growth of intra-EU trade.
2. The **strengthening of maritime transport** until 2022, followed by an adjustment due to geopolitical tensions and fluctuations in global logistics costs.
3. The **rise of rail transport** as a sustainable alternative, in line with **EU carbon emission reduction policies**.
4. The **vulnerability of river transport** to climate change and infrastructure limitations.

These developments confirm the **need for an integrated logistics and foreign trade strategy**, based on the **diversification of transport routes** and the **optimization of multimodal infrastructure**, aligned with **European trends in circular economy and sustainability** (*Tanasiichuk et al., 2025; INS, 2025*).

2. FOB export values by commodity groups according to the Combined Nomenclature (CN)

The analysis of exports by **commodity groups** provides a detailed overview of the structure of Romanian products traded internationally, highlighting **sectoral specialization trends** and the **geographical orientation** of trade flows.

According to data provided by the **National Institute of Statistics (INS)**, the period **2020–2024** shows **significant variations** in the export of **live animals**, a category of high relevance for Romania's **agricultural and livestock trade** (*INS, 2025*).

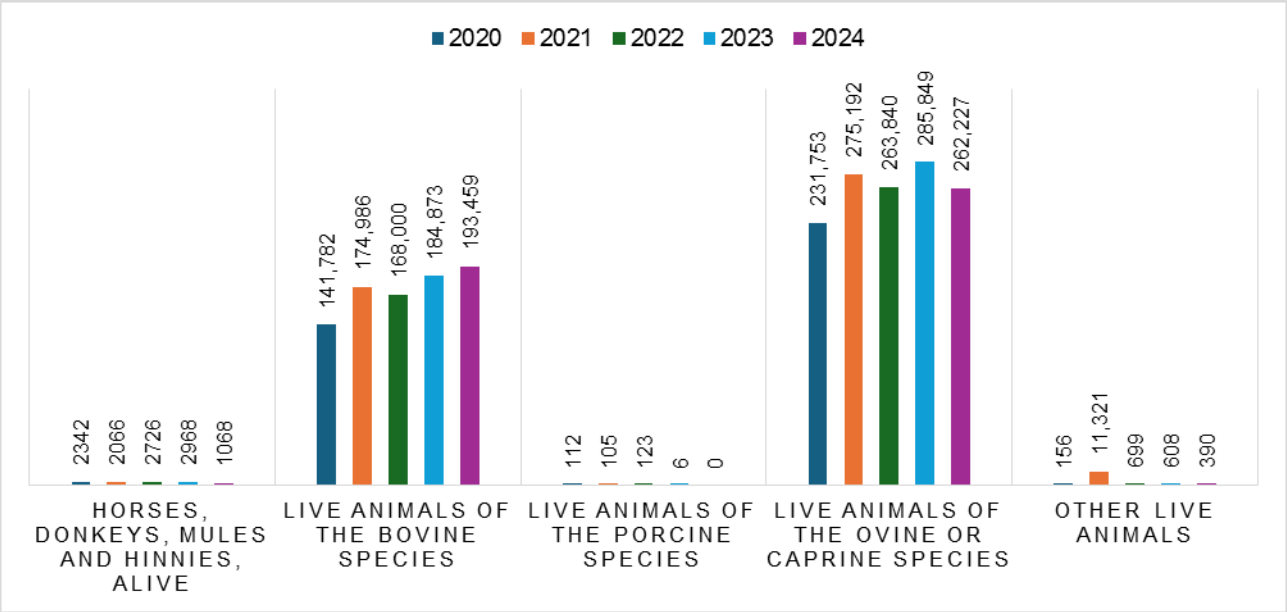

Fig. 2 - FOB export value by commodity groups, U.M. = thousand euros
(NIS, http://statistici.insse.ro)

The data show that live sheep and goat exports consistently dominate the analyzed category, with values ranging from €231.7 million (2020) to a peak of €285.8 million (2023). This confirms Romania's position as the main exporter of live sheep in Central and Eastern Europe, with destinations primarily in Arab and Southern European countries (*Ilie, 2024; European Court of Auditors, 2023*).

Live cattle exports also displayed a positive evolution, increasing from **€141.8 million in 2020** to **€193.4 million in 2024**, reflecting a **stable external demand**, particularly from **Turkey, Italy, and Spain** (*Miu and Strâmbovschi, 2025*).

The category of **live pigs** experienced a **sharp contraction**, dropping from marginal levels during **2020–2022** to **zero exports in 2024**, a decline attributable to **sanitary restrictions** caused by the **African Swine Fever (ASF)** outbreak and the **loss of access to several external markets** (*Hristova-Politikova, 2025*).

Equine exports (horses, donkeys, and mules) remained insignificant, recording a **64% decrease in 2024 compared to 2023**, which indicates a **structural decline** in this niche market. In contrast, the **"other live animals"** category exhibited **high volatility**, with an abnormal spike in **2021 (€11.3 million)** followed by a return to lower levels — possibly due to **statistical reclassification** or **occasional extra-EU exports** (*Tanasiichuk et al., 2025*).

3. FOB export value by sections and chapters according to the Combined Nomenclature (CN): total and for the European Union

This section presents the **structure of Romania's exports** according to the main **sections and chapters of the Combined Nomenclature (CN)**, offering a **comparative perspective** between **total exports** and those **directed toward the European Union (EU)**. The data reflect the **degree of integration of the Romanian economy** within the **European Single Market**, as well as the **role of non-EU markets** in the diversification of exports (*INS, 2025*).

Table 1

FOB export value – total and for the European Union

(NIS, http://statistici.insse.ro)

Sections and chapters according to the Combined Nomenclature (CN)	European Union	2020	2021	2022	2023	2024
		U.M.: mii EURO				
Live animals and animal products	Overall	845,171	1,020,920	1,146,236	1,228,559	1,320,359
	Of the total: European Union	464,820	566,280	686,228	730,615	809,213
Live animals	Overall	405,621	492,885	475,076	524,558	504,773
	Of the total: European Union	130,553	154,573	159,122	184,986	163,165
Other animal products	Overall	24,779	34,707	37,126	33,353	29,023
	Of the total: European Union	21,121	29,327	31,475	27,551	22,799
Plant products	Overall	3,351,217	5,431,052	6,750,383	6,641,623	4,744,884
	Of the total: European Union	1,687,247	2,605,688	3,542,438	3,324,816	2,391,186
Animal or vegetable fats and oils	Overall	194,977	359,405	639,530	446,566	347,136
	Of the total: European Union	136,292	248,218	513,520	264,032	262,156

The data show a **significant increase in Romania's exports across all major categories** during the period **2020–2022**, followed by relative stabilization in **2023** and a **slight contraction in 2024**, against the background of **slowing external demand** and the **reconfiguration of European markets**.

a) Animal products and live animals

The total export value of animal products increased from **€845 million in 2020** to **€1.32 billion in 2024** (+56%). Among these, **live animals account for more than 38%** of the total category, although only about **one-third** of them are exported within the EU (**32.3% in 2024**). This confirms Romania's traditional orientation toward **non-EU markets** such as **Turkey, Jordan, and Saudi Arabia**, where the demand for live animals remains high (*European Court of Auditors, 2023*).

b) Plant products

This category represents the **most valuable component** of Romania's export structure, peaking at **€6.75 billion in 2022**, followed by a decline to **€4.74 billion in 2024 (−30%)**. The decrease can be associated with **fluctuations in grain and oilseed prices**, as well as **logistical restrictions** generated by the **war in Ukraine**, which affected trade flows through the **Black Sea corridor**. Nevertheless, approximately **half of these**

exports (≈50%) continue to be directed toward **EU Member States**, confirming the **deep integration of Romania's agricultural sector** into **European food supply chains**.

c) Animal and vegetable fats and oils

This category experienced the **steepest relative growth**, from **€195 million in 2020** to **€639 million in 2022 (+227%)**, followed by a gradual adjustment to **€347 million in 2024**. The evolution is closely linked to the **expansion of sunflower oil exports**, a sector in which **Romania became a regional leader**, and to **seasonal variations in international oilseed prices**. The share directed to the **EU (75.5%)** indicates a **strong dependence** on the European market but also a **vulnerability** to its trade policies and sustainability standards.

Observed structural trends

1. **Increasing dependence on the EU market**, which accounts for over **60% of total analyzed exports**.
2. **Decline in plant-based exports after 2022**, driven by logistical crises and price volatility.
3. **Geographical diversification** of live animal exports, with a clear shift toward **non-EU destinations**.
4. **Enhanced sustainability** in the trade of animal and plant-based products, under pressure from **European Green Deal policies** (*European Court of Auditors, 2023*).

4. Romania's main trading partners (2020–2024)

The analysis of Romania's exports by **partner countries** highlights a **high concentration of trade flows within the European Union (EU)**, which remains the **main destination** for Romanian goods. According to official data from the **National Institute of Statistics (INS)**, between **2020 and 2024**, over **72% of Romania's total export value** was directed to **EU Member States** (*INS, 2025*).

Table 2

Top 50 – FOB export value by partner countries

(NIS, http://statistici.insse.ro)

Ranking	Countries	2020	2021	2022	2023	2024	Overall 2022-2024
		U.M.: thousand euros					
1	Germania	14,155,522	15,335,171	18,258,950	19,399,639	19,041,998	86,191,280
2	Italia	6,670,419	7,814,493	9,261,347	9,467,533	8,847,903	42,061,695
3	Franța	4,175,637	4,771,084	5,535,077	5,908,539	5,867,429	26,257,766
4	Ungaria	3,096,081	4,245,896	6,787,881	5,271,247	4,922,842	24,323,947
5	Bulgaria	2,257,927	2,927,149	3,562,759	3,869,082	4,106,638	16,723,555
6	Polonia	2,316,586	2,977,915	3,499,726	3,424,162	3,713,756	15,932,145
7	Olanda	2,195,670	2,567,052	3,223,363	3,147,221	3,376,260	14,509,566
8	Turcia	2,100,205	2,622,781	2,819,132	3,061,208	3,324,408	13,927,734
9	Republica Cehă	1,922,858	2,337,840	2,656,612	2,998,266	3,086,703	13,002,279
10	Spania	1,838,612	2,227,494	2,866,090	3,004,097	2,879,264	12,815,557
11	Regatul Unit	2,073,359	2,150,318	2,633,329	2,737,159	2,900,945	12,495,110
12	Austria	1,474,987	1,887,838	2,213,025	1,982,181	1,884,841	9,442,872
13	Statele Unite	1,071,621	1,559,953	2,265,277	2,150,184	2,285,548	9,332,583
14	Republica Moldova	1,032,697	1,301,656	2,266,392	2,075,437	2,255,873	8,932,055
15	Belgia	1,223,934	1,588,885	1,880,555	2,220,887	1,875,554	8,789,815
16	Slovacia	1,334,333	1,592,246	1,788,076	2,018,317	2,045,438	8,778,410
17	Ucraina	587,097	706,510	1,544,291	2,474,065	1,872,465	7,184,428
18	Serbia	711,088	981,143	1,485,362	1,324,568	1,186,330	5,688,491
19	Grecia	699,040	890,137	1,079,516	1,092,639	1,238,235	4,999,567
20	China	829,196	1,134,446	1,083,159	856,682	719,439	4,622,922
21	Elveția	595,506	557,053	668,467	755,112	1,381,792	3,957,930
22	Maroc	455,165	579,183	785,671	927,076	986,647	3,733,742
23	Suedia	529,238	624,023	770,188	751,436	746,623	3,421,508
24	Japonia	447,873	394,016	661,108	761,190	773,122	3,037,309
25	Egipt	393,978	780,869	765,621	541,177	460,642	2,942,287
26	Israel	431,289	576,632	777,213	403,839	504,263	2,693,236
27	Federația Rusă	820,917	1,019,120	399,377	236,241	184,256	2,659,911
28	Norvegia	465,637	541,476	405,340	338,417	651,550	2,402,420

29	**Arabia Saudită**	395,199	305,329	323,629	573,506	783,373	2,381,036
30	**Portugalia**	271,843	357,021	543,043	567,162	532,241	2,271,310
31	**Slovenia**	372,666	431,989	466,963	427,597	470,772	2,169,987
32	**Iordania**	251,436	402,159	622,228	347,848	305,650	1,929,321
33	**Croația**	251,668	299,027	416,839	426,631	508,332	1,902,497
34	**Danemarca**	300,629	338,137	408,558	368,064	339,197	1,754,585
35	**Coreea Sud**	226,351	369,988	402,046	535,960	196,521	1,730,866
36	**Emiratele Arabe Unite**	196,493	250,369	429,918	402,575	351,597	1,630,952
37	**India**	154,954	229,775	282,811	321,739	269,369	1,258,648
38	**Mexic**	182,281	202,421	246,145	262,757	304,847	1,198,451
39	**Finlanda**	204,087	213,054	245,351	207,099	226,197	1,095,788
40	**Macedonia de Nord**	186,915	240,729	216,622	192,546	195,914	1,032,726
41	**Tunisia**	148,727	251,377	281,734	173,683	135,102	990,623
42	**Canada**	92,162	260,753	194,127	221,647	155,946	924,635
43	**Irlanda**	122,520	166,695	172,697	213,929	243,840	919,681
44	**Lituania**	110,846	168,975	211,251	199,602	204,720	895,394
45	**Gibraltar**	149,949	151,757	230,552	129,276	220,848	882,382
46	**Brazilia**	134,197	150,372	178,995	170,323	216,157	850,044
47	**Liban**	190,939	143,790	202,091	92,117	158,213	787,150
48	**Africa de Sud**	140,621	183,755	160,797	136,851	108,982	731,006
49	**Libia**	88,125	83,685	151,891	202,429	93,010	619,140
50	**Filipine**	118,083	24,277	8614	21,247	11,080	183,301

Comparative analysis: EU vs. Non-EU

Romania conducts the **majority of its international trade within the European Union**, accounting for **over 70% of total FOB exports**. The main destination markets — **Germany, Italy, and France** — together represent **more than 45% of Romania's exports to the EU**, reflecting the country's **deep integration into Western European value chains**.

Among **non-EU partners**, **Turkey** stands out clearly as Romania's **largest extra-community partner**, with total exports of nearly **€14 billion** during the analyzed period. Other relevant markets include the **United States (€9.33 billion)**, **the Republic of Moldova (€8.93 billion)**, and **Ukraine (€7.18 billion)**, each showing significant dynamism within the current regional context (*Busu and Ene, 2025*).

Intermediate Conclusions

1. **Germany** remains by far **Romania's main trading partner**, accounting for **almost 21% of total exports** between 2020 and 2024.
2. **Italy and France** confirm the **structural orientation** of Romanian trade toward the **Western European market**.
3. **Turkey, the United States, and the Republic of Moldova** have emerged as key **non-EU destinations**, reflecting a **strategic diversification** of exports.
4. The **decline in exports to China and Russia** (−13% and −77%, respectively) reflects Romania's **geopolitical repositioning** under the new **EU trade policy framework**.
5. **General trend (2020–2024):** strengthening regional partnerships and **rebalancing exports** between **mature EU markets** and **emerging non-EU markets**.

Overall Interpretation

The overall analysis of Romania's exports between **2020 and 2024** highlights an **upward trajectory**, yet one marked by **structural adjustments** to regional economic and geopolitical realities. Total exports increased by **nearly 50%** in five years, supported by the expansion of **intra-EU trade** and the **diversification of economic relations** with non-EU markets. Romania has consolidated its position within **European value chains**, through exports focused on **industrial goods, agricultural products, and automotive components**. However, its **strong dependence on the EU market** remains a **strategic vulnerability** in the face of external shocks. At the same time, the **logistical reconfiguration** (rising shares of **rail and maritime transport**) and the **structural adaptation** of agricultural and energy exports confirm Romania's ongoing **alignment with the principles of the Green Economy** and with the objectives of the **European Trade Policy** (*Miu and Strâmbovschi, 2025*).

In the **medium term**, the positive dynamics of exports will depend on Romania's ability to **modernize transport infrastructure**, **increase industrial competitiveness**, and **maintain stable access to external markets** in a volatile geopolitical environment. Thus, the **2020–2024 period** can be considered a **phase of maturity** for Romania's foreign trade, characterized by **consolidation, diversification, and strategic repositioning** within both the **European and global context**.

S.W.O.T. analysis

The S.W.O.T. analysis provides a **strategic synthesis of Romania's position in international trade**, taking into account export performance by sector, destination, and mode of transport, as well as the **structural, economic, and geopolitical factors** influencing external competitiveness.

a) Strengths

1. Steady growth in total export value, from €62.1 billion (2020) to €92.6 billion (2024), indicating a strengthening of external competitiveness.
2. Strong integration into European value chains, with over 70% of exports directed toward the European Union, particularly Germany, Italy, and France.
3. Diversification of non-EU markets, with notable export growth to Turkey (+58%), the Republic of Moldova (+118%), and the United States (+113%).
4. Remarkable agricultural performance, especially in plant products (grains, oils, oilseeds), positioning Romania as a strategic regional exporter.
5. Competitive regional road transport infrastructure, with 68% of FOB exports carried by road in 2024.
6. Resilience to external shocks, demonstrated by the adaptation of trade flows after the COVID-19 pandemic and amid the Ukraine conflict.

b) Weaknesses

1. Structural dependence on the EU market, exposing exports to fluctuations in demand and EU trade policy.
2. Logistical and infrastructural deficiencies, particularly in rail and inland waterway transport, limiting cost efficiency.
3. Export concentration in low value-added sectors (raw agricultural products, primary goods, live animals).
4. Price volatility in agricultural products and vulnerability to climatic and environmental factors.
5. Limited industrial capacity for technological exports, compared to other Central and Eastern European economies.
6. Insufficient digitalization and innovation in foreign trade, reducing logistical competitiveness and adaptability to the global digital economy.

c) Opportunities

1. Rising global demand for agri-food and energy products, from which Romania can benefit amid the reorientation of global supply chains.
2. European investments in transport and logistics infrastructure (e.g., *Rhine–Danube Corridor*, *Three Seas Initiative*), which may reduce export costs (*Ministry of Investments and European Projects, 2020; Three Seas Summit Warsaw, 2025*).
3. Expansion of green exports — biofuels, energy equipment, and sustainable products — under the European Green Deal.
4. Extension of trade relations with emerging markets in Asia and the Middle East, where Romania already has consolidated partnerships (Turkey, Saudi Arabia, United Arab Emirates).
5. Growing integration into digital trade and cross-border e-commerce, supported by EU funds through the Digital Europe Programme.
6. Potential regional repositioning as a Black Sea logistics hub, particularly in the context of post-conflict reconstruction in Ukraine.

d) Threats

1. Regional geopolitical instability (the war in Ukraine, global trade tensions), which could disrupt logistics flows and maritime exports.
2. Rising global protectionism, with potential tariff and non-tariff barriers in non-EU markets.
3. Energy and fuel price volatility, affecting transport costs and export competitiveness.
4. Dependence on road infrastructure, creating vulnerability to energy and environmental crises.
5. Risk of losing traditional markets to lower-cost producers (e.g., Ukraine, Serbia, Turkey).

6. Stringent EU environmental and sustainability regulations, potentially increasing compliance costs for local exporters.

The S.W.O.T. analysis highlights a **consolidated yet strategically recalibrating trade position**. Romania holds **significant advantages** in the agricultural and logistics sectors, but **external competitiveness** depends on its ability to:

- **increase the value-added component** of exports;
- **improve rail and port infrastructure**; and
- **accelerate the transition toward digital and green trade**.

Thus, the **balance between structural dependence on the EU** and the **need for extra-European diversification** will define the **future direction of Romania's international trade** over the next decade.

CONCLUSIONS

The analysis of Romania's exports for the period 2020–2024 highlights a positive and adaptable dynamic of foreign trade, despite a global economic context marked by instability. FOB exports increased from €62.1 billion in 2020 to €92.6 billion in 2024, consolidating Romania's position as a competitive regional actor within both the European Union and neighboring markets.

The main conclusions can be summarized as follows:

1. **Sustained and diversified export growth** – Romania recorded significant expansion across all major product categories, with a dominant contribution from the **industrial** and **agricultural sectors**.
2. The **European Union market remains essential**, accounting for **over 70%** of total exports; **Germany, Italy, and France** continue to be Romania's key trading partners.
3. **Geographical diversification** toward **non-EU markets** (Turkey, the Republic of Moldova, the United States, and Ukraine) indicates a **strategic trend to reduce dependence** on the single European market.
4. **Road transport remains the dominant export mode** (over **68%** of total value), but the gradual increase in **rail and maritime transport** reflects the **modernization of logistics infrastructure**.
5. The **commodity structure** reveals a **growing share of plant-based products and oils**, although **high value-added exports** remain below the **EU average**.
6. The **geopolitical and economic context** (the pandemic, the war in Ukraine, and climate change) influenced export dynamics, yet Romania demonstrated **resilience and adaptability**.

In the medium term, maintaining this **positive trajectory** will depend on:

- **improving multimodal transport infrastructure** (rail, river, and port systems);
- **developing industrial and technological capacities** with higher value-added potential;
- **advancing the digitalization and greening of foreign trade**, in line with the **European Green Deal objectives**; and
- **expanding extra-European trade partnerships**, particularly in **Asia and the Middle East**.

Therefore, the **2020–2024 period** can be regarded as a **phase of strategic transition and maturity** in Romania's export development, marking a shift from a **resource-based economy** to one oriented toward **competitiveness, sustainability, and diversification** within the international market.

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TRENDS OF UNEMPLOYMENT IN ROMANIA (2020–2024): A STATISTICAL, REGIONAL, AND EDUCATIONAL PERSPECTIVE

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EVOLUȚIA ȘOMAJULUI ÎN ROMÂNIA (2020–2024): ANALIZĂ STATISTICĂ, REGIONALĂ ȘI EDUCAȚIONALĂ

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ABSTRACT

This study analyzes the evolution and dynamics of unemployment in Romania during the period 2020–2024, with a focus on the regional, educational, and occupational dimensions of the labor market. The analysis is based on official statistical data provided by the National Institute of Statistics (INS), using datasets SOM101B–SOM104A, and complemented by reports from the National Employment Agency (ANOFM). All data were processed using Microsoft Excel 365, through which comparative tables, trend graphs, and thematic maps were developed to illustrate the territorial disparities in unemployment. The results reveal a relatively low overall unemployment rate (2–4%) but significant regional and structural disparities: the western regions and Bucharest–Ilfov recorded the lowest levels, while South-West Oltenia and North-East remained the most vulnerable areas. The analysis also emphasizes the influence of education level on employability and the positive, albeit limited, impact of vocational training programs on employment outcomes. Through the integration of findings into a S.W.O.T. analysis, the study identifies the main strengths, weaknesses, opportunities, and threats shaping the Romanian labor market, offering a strategic overview of future development directions. The conclusions highlight the need to strengthen training and retraining policies, reduce regional imbalances, and align the education system with the demands of a modern, digital economy.

REZUMAT

Acest studiu analizează evoluția și dinamica șomajului în România în perioada 2020–2024, punând accent pe dimensiunile regionale, educaționale și ocupaționale ale pieței muncii. Analiza utilizează date statistice oficiale furnizate de Institutul Național de Statistică (INS), prin seriile de indicatori SOM101B–SOM104A, completate cu informații din rapoartele Agenției Naționale pentru Ocuparea Forței de Muncă (ANOFM). Datele au fost prelucrate și sintetizate cu ajutorul aplicației Microsoft Excel 365, fiind realizate tabele comparative, grafice evolutive și hărți tematice care surprind diferențele teritoriale ale șomajului. Rezultatele indică o rată generală a șomajului relativ scăzută (2–4%), dar marcată de disparități regionale și structurale semnificative: regiunile vestice și București–Ilfov au înregistrat valori minime, în timp ce Sud-Vest Oltenia și Nord-Est au rămas zone vulnerabile. De asemenea, analiza evidențiază influența nivelului de educație asupra reinserție profesionale și rolul pozitiv, deși limitat, al cursurilor de formare profesională asupra ocupării. Prin integrarea rezultatelor într-o analiză S.W.O.T., studiul identifică principalele puncte forte, slăbiciuni, oportunități și amenințări ale pieței muncii românești, oferind o perspectivă strategică asupra direcțiilor de dezvoltare viitoare. Concluziile subliniază necesitatea consolidării politicilor de formare și recalificare, reducerea dezechilibrelor regionale și adaptarea sistemului educațional la cerințele economiei moderne și digitale.

INTRODUCTION

Unemployment represents one of the main indicators of a country's economic and social balance, being closely linked to labor market dynamics, the level of education, and the economy's capacity to generate sustainable jobs. In Romania, the period 2020–2024 was marked by a series of events that significantly influenced the structure of employment: the health crisis generated by the COVID-19 pandemic,

the accelerated transition toward digitalization, the instability of the energy market, and demographic changes in both rural and urban environments.

Although the average unemployment rate remained at a low level compared to other European Union member states, the reality behind these figures reveals significant **regional and social disparities**. The more developed regions in the western part of the country and the Bucharest–Ilfov area benefited from a constant demand for labor and sustained investment in modern sectors, while the southern and eastern regions continue to face structural difficulties, limited economic infrastructure, and a lower level of education and vocational qualification.

At the same time, the level of education and access to vocational training have become key determinants of labor market reintegration. The retraining programs implemented by the **National Employment Agency (ANOFM)** and financed through European funds have contributed to the partial reintegration of the unemployed into economic activities, although their impact remains uneven across regions.

This study aims to provide a **comprehensive analysis of the dynamics of unemployment in Romania between 2020 and 2024**, based on official data from the **National Institute of Statistics (INS)**, examining regional trends, age and education distribution, and the correlation between vocational training and employment. Furthermore, the analysis is complemented by a **S.W.O.T. evaluation** of the labor market, highlighting the main strengths, weaknesses, opportunities, and threats faced by the Romanian economy in the current context.

MATERIALS AND METHODS

The statistical analysis of unemployment trends in Romania for the period 2020–2024 was conducted based on official data provided by the National Institute of Statistics (INS) through the TEMPO Online database.

The following sets of indicators were used, coded according to the INS classification system:

- **SOM101B** – Registered unemployed persons by development regions (number of persons)
- **SOM101C** – Registered unemployed beneficiaries of unemployment benefits, by age group, gender, and education level
- **SOM101D** – Registered unemployed beneficiaries of unemployment benefits, by unemployment duration, age group, and gender
- **SOM103A** – Unemployment rate by development regions (percentages)
- **SOM104A** – Participants in vocational training courses (number of persons)

All data were downloaded and verified in **2025** for the reference period **2020–2024** and processed using **Microsoft Excel 365**. The software was employed for the following purposes:

- organizing statistical data series;
- developing the numerical tables presented in the *Results* section;
- creating comparative charts using built-in *Column Chart* and *Line Chart* functions;
- generating thematic maps of Romania (development regions) through the *Map Chart* and *Conditional Formatting* tools to highlight regional differences in unemployment levels.

To ensure data consistency, the INS results were compared with those of the **National Employment Agency (ANOFM)** and the **Eurostat** datasets available for the same period. All data sources were selected exclusively from official publications or publicly accessible databases, with no alterations made to numerical values.

The interpretation of data followed a **descriptive-analytical approach**, focusing on the identification of temporal and regional unemployment trends, as well as on the relationship between unemployment, educational attainment, and participation in vocational training programs. In addition, methodological comparisons were made with the study conducted by *Cruceru and Nijloveanu (2021)*, which analyzed the period **2015–2020**, in order to highlight continuities and structural changes within the Romanian labor market. This previous study served as a **conceptual and comparative reference**, contributing to the validation of the analytical directions adopted in the present research.

The applied methodology ensures **transparency, reproducibility, and scientific coherence**, allowing for a clear integration between statistical data, empirical analysis, and socio-economic interpretation.

RESULTS

The analysis of unemployment indicators in Romania for the period **2020–2024**, based on official data from the **National Institute of Statistics (INS)**, highlights significant differences between development regions, educational levels of registered unemployed persons, and the influence of participation in vocational training programs on employment opportunities. The results are structured to allow both a **comparative numerical presentation** (tables) and a **graphical or map-based visualization** of territorial disparities.

In the academic literature, it has been shown that **education level and vocational training** can have a substantial impact on labor market participation and employability (*Diaconu, 2014; Popescu and Roman, 2018*). Based on these premises, the following subsection presents the first analytical dimension of the study:

a) Unemployment rate by development regions (2020–2024, U.M. = Percentages)

The data provided by the **National Institute of Statistics (INSSE)** indicate a relatively stable overall unemployment rate for the period 2020–2024, but with pronounced disparities among development regions.

The values range from a minimum of **0.6% in the Bucharest–Ilfov Region (2024)** to a maximum of **6.1% in the South-West Oltenia Region**, confirming the persistent contrast between urbanized economic areas and predominantly agricultural or declining industrial regions.

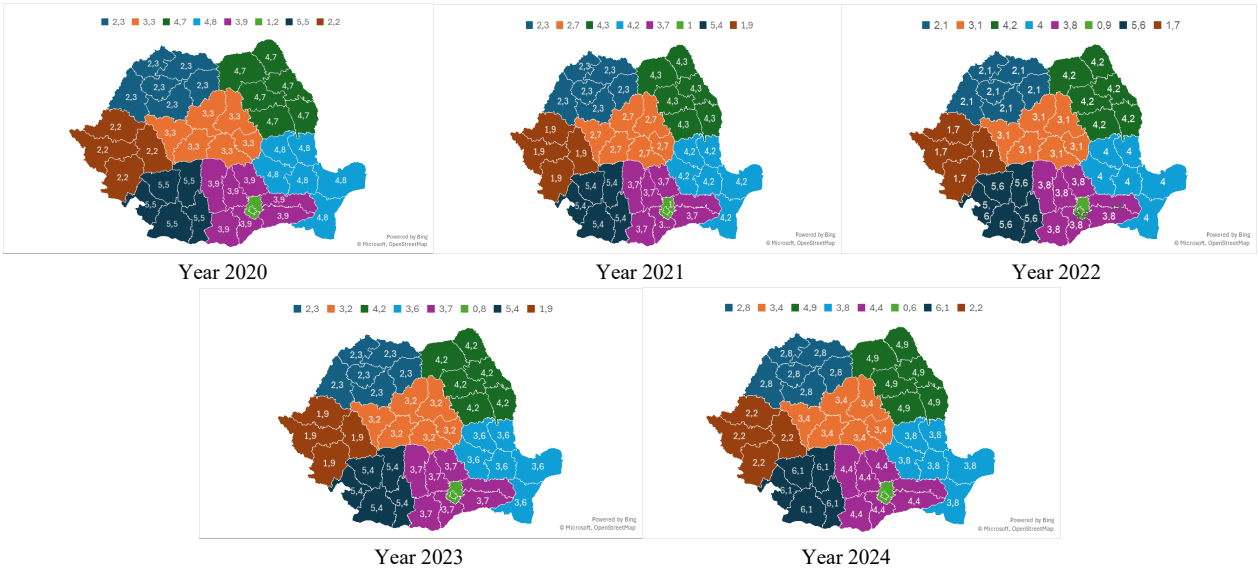

Fig. 1 - Unemployment rate by development regions, displayed through interactive maps for each reference year *(NIS, http://statistici.insse.ro)*

The overall trend shows a slight increase in unemployment in 2024 compared to 2022–2023, but with clear regional variations.

- The **Bucharest–Ilfov Region** continues to demonstrate the strongest labor market performance during this period, maintaining an unemployment rate below 1%, a result explained by the concentration of service sectors and foreign direct investments.
- The **South-West Oltenia Region** remains the area with the highest unemployment rate (6.1% in 2024), which correlates with its traditional industrial structure and the low absorption rate of the requalified labor force (*Cruceru and Nijloveanu, 2021*).
- In the **North-East** and **South-East Regions**, unemployment values exceed 4%, reflecting historical development gaps and the high share of seasonal occupations.
- Conversely, the **West** and **North-West Regions** maintain low unemployment levels (below 3%), due to their attractiveness for foreign investments and cross-border labor mobility.

Compared with the 2015–2020 period — when, according to *Cruceru and Nijloveanu (2021)*, Mehedinți and Olt counties recorded peak levels (over 10%) — the current data show an **average decrease of 4–5 percentage points**. However, the gap between eastern and western regions persists. This constant disparity confirms the existence of a ***"geography of unemployment"*** in Romania, where the southern and eastern parts of the country remain vulnerable to structural changes in the labor market.

Specialized studies have underlined that **regional development policies and vocational training** are essential tools for reducing these discrepancies (*Popescu and Roman, 2018*).

The reasons for the unemployment of a rural settlement are, first of all, the reduction of enterprises associated with the production and processing of agricultural products. Partial or complete cessation of the work of many agricultural industries, slowdown in the creation of new ones, modernization and reconstruction of existing ones (*Volokhova, 2022*).

General observations

1. In all regions, **2021–2022** marks a period of post-pandemic recovery, followed by a **slight increase in 2024**.
2. **Regional disparities persist**, with the ratio between the highest and lowest unemployment rates being approximately **10 to 1 (6.1% vs 0.6%)**.
3. Regions with low unemployment coincide with **emerging economic centers** (Cluj-Napoca, Timișoara, Brașov), confirming the **correlation between investment levels and employment**.

b) Registered unemployed by development regions (Romania, 2020–2024, U.M. = Number of persons)

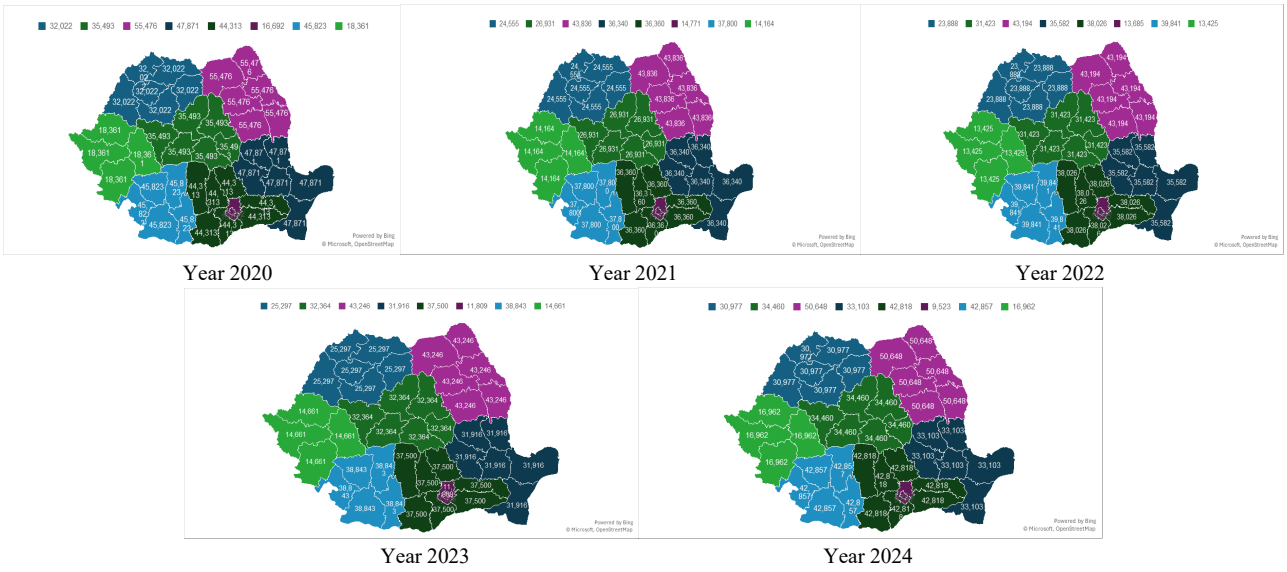

Fig. 2 - Number of registered unemployed persons by development regions, displayed through interactive maps for each reference year

(NIS, http://statistici.insse.ro)

The data reveal a relatively stable dynamic in the total number of unemployed persons between 2020 and 2024, yet persistent structural differences among Romania's historical regions. The number of jobless individuals remains consistently higher in the North-East and South-West Oltenia regions, while Bucharest–Ilfov continues to record the lowest values, confirming the inverse relationship between the level of economic development and unemployment.

In **2024**, the **North-East Region** registered the highest absolute number of unemployed persons (≈ **50,600**), followed by **South-West Oltenia** (≈ **42,800**) and **South-Muntenia** (≈ **42,800**). At the opposite end, the **Bucharest–Ilfov Region** recorded fewer than **10,000 unemployed persons**, a **reduction of over 40%** compared to 2020.

These differences can be explained by several structural factors:

- **Industrial distribution and regional infrastructure** – older industrial zones (Oltenia, South-Muntenia) were more affected by economic restructuring;
- **High rural population share** – in the North-East and South-East, agriculture and seasonal work dominate, reducing employment stability (*Diaconu, 2014*);
- **The concentration of services and foreign direct investment (FDI)** in the western regions and the capital.

Trends in the period 2020–2024

- Between **2020 and 2021**, there was a **sharp decline** in unemployment across all regions, driven by post-pandemic economic recovery.

- During **2022–2023**, the trend stabilized, but **2024** showed a **moderate increase**, more pronounced in the **North-West (+22%)** and **North-East (+17%)**, likely due to labor market rigidity and the broader slowdown of the European economy.
- The **West** and **Bucharest–Ilfov** regions show the most stable employment levels, where **service- and IT-oriented economic structures** reduce vulnerability to external economic shocks.

Comparison with the 2015–2020 period

According to the previous study by *Cruceru and Nijloveanu (2021)*, the highest absolute unemployment levels were also recorded in **Mehedinți, Dolj, and Olt** — counties that are part of the South-West Oltenia region — confirming the persistence of regional gaps. Although absolute figures in **2024** are **20–30% lower** than those reported in **2015–2020**, the **territorial distribution of unemployment remains unchanged**, revealing a **structural rather than conjunctural problem**.

General observations

1. **Regional disparities** remain consistent between 2020–2024, with a difference of over **40,000 persons** between the extreme regions.
2. The **employment structure** favors regions with strong service, tourism, and IT activities, to the detriment of those dependent on heavy industry and agriculture.
3. **Requalification and vocational training policies** should be concentrated in the **North-East** and **South-West**, where the potential for unemployment reduction is the highest.

c) Structure of unemployed persons by age and gender, according to unemployment duration

Table 1

Number of registered unemployed persons – beneficiaries of unemployment benefits, by duration of unemployment and gender

(NIS, http://statistici.insse.ro)

Age groups	Duration of unemployment	Genders	2020	2021	2022	2023	2024
			U.M.: Number of persons				
Overall	1 day - 6 months	Male	30,268	16,861	15,072	53,450	16,849
		Female	40,983	19,732	19,325	56,328	24,131
	1 day - 3 months	Male	15,655	9259	9740	30,142	9769
		Female	19,274	9546	11,416	30,176	12,878
	3 to 6 months	Male	14,613	7602	5332	23,308	7080
		Female	21,709	10,186	7909	26,152	11,253
	6 to 12 months	Male	11,089	6380	4758	20,844	6837
		Female	18,400	9140	6376	21,378	10,307
	6 to 9 months	Male	6097	3307	2690	10,322	3387
		Female	10,110	4799	3817	11,053	5473
	9 to 12 months	Male	4992	3073	2068	10,522	3450
		Female	8290	4341	2559	10,325	4834
Under 25 years of age	1 day - 6 months	Male	4625	3129	2672	12,052	2845
		Female	5697	3661	3105	12,916	3186
	1 day - 3 months	Male	1715	633	875	4988	942
		Female	1878	797	1122	5081	1143
	3 to 6 months	Male	2910	2496	1797	7064	1903
		Female	3819	2864	1983	7835	2043
	6 to 12 months	Male	689	62	0	1500	30
		Female	587	31	5	1229	16
	6 to 9 months	Male	378	58	0	775	25
		Female	374	31	4	703	11
25 years and older	1 day - 6 months	Male	25,643	13,732	12,400	12,052	14,004
		Female	35,286	16,071	16,220	12,916	20,945
	6 to 12 months	Male	10,400	6318	4758	19,344	6807
		Female	17,813	9109	6371	20,149	10,291
Aged 25-29	1 day - 3 months	Male	811	386	408	2510	415
		Female	1258	475	607	2900	637
	3 to 6 months	Male	614	189	136	1707	185
		Female	1122	402	305	2294	401

	6 to 9 months	Male	205	68	22	490	46
		Female	411	136	55	497	88
	9 to 12 months	Male	191	24	0	485	10
		Female	230	45	0	400	14
Aged 30-39	1 day - 3 months	Male	2427	1436	1425	5261	1411
		Female	3691	1714	2024	5038	2161
	3 to 6 months	Male	1875	733	516	3188	732
		Female	3734	1535	1335	3770	1731
	6 to 9 months	Male	913	392	277	1588	419
		Female	2041	874	619	1896	819
	9 to 12 months	Male	918	241	108	1486	236
		Female	1449	473	212	1382	352
Aged 40-49	1 day - 3 months	Male	4198	2782	2736	6783	2537
		Female	5913	2887	3290	7140	3523
	3 to 6 months	Male	3215	1617	1035	4316	1388
		Female	5520	2306	1818	5053	2690
	6 to 9 months	Male	1965	864	760	2517	893
		Female	3586	1545	1177	3071	1571
	9 to 12 months	Male	1796	806	507	2678	828
		Female	2777	1409	712	2908	1319
Aged 50-55	1 day - 3 months	Male	3302	2348	2179	5125	2095
		Female	4405	2476	2484	5546	2852
	3 to 6 months	Male	2701	1395	964	3248	1239
		Female	4383	1983	1611	4046	2212
	6 to 9 months	Male	1418	1008	868	2045	839
		Female	2869	1408	1252	2598	1467
	9 to 12 months	Male	1613	950	737	2164	907
		Female	2540	1524	1044	2595	1467
Over 55 years old	1 day - 3 months	Male	3202	1674	2117	5475	2369
		Female	2129	1197	1889	4471	2562
	3 to 6 months	Male	3388	1172	884	3785	1633
		Female	3131	1096	857	3154	2176
	6 to 9 months	Male	1218	917	763	2907	1165
		Female	829	805	710	2288	1517
	9 to 12 months	Male	163	1048	716	2984	1464
		Female	1081	890	590	2514	1677

Statistical data indicate that between **2020 and 2024**, the share of **women among unemployment benefit recipients** remained higher than that of men, particularly in short-term unemployment categories (under six months). On average, women represented approximately **57–60%** of all compensated unemployed persons — a proportion consistent with historical patterns observed during the **2015–2020** period (*Cruceru and Nijloveanu, 2021*).

Throughout the analyzed period, two clear trends can be observed:

1. A **temporary increase** in the total number of compensated unemployed persons in **2023**, the year of post-pandemic recovery, followed by a sharp decline in **2024**;
2. An **increase in the average duration of unemployment** among individuals over 40 years old, compared to younger groups (under 25), who experience faster reintegration but also greater employment volatility.

Age distribution

1. **Young people under 25 years old**
   - Showed major fluctuations: from **4625 men in 2020** to a peak of **12,052 in 2023**, then a drop to **2845 in 2024**.
   - This behavior confirms the **seasonal nature of youth employment** and their vulnerability to economic shocks.
   - Women under 25 recorded similar levels (**12,916 in 2023**), suggesting a **relatively balanced gender distribution** in this age group.

2. **Adults aged 25–49 years**
   - Represent the **largest segment** of the unemployed population, with annual averages exceeding **30,000 persons**.
   - However, a **shortening of unemployment duration** is observed after 2021, mainly due to **requalification and reintegration programs**.
3. **People over 55 years old**
   - Exhibit a **longer unemployment duration** (over six months in most cases), with increasing reintegration difficulties, as confirmed by specialized studies.
   - Women in this category **outnumber men** (**2562 vs. 2369 in 2024**), reflecting both a longer professional lifespan and a **higher risk of labor market marginalization**.

Unemployment duration and temporal trends

Unemployment duration shows a **dual distribution** pattern:

- **Short-term unemployment (1–6 months)** – predominant (≈ **70%** of total), suggesting a relatively **flexible labor market** and moderate reintegration capacity;
- **Long-term unemployment (6–12 months)** – increased significantly in **2023**, likely as a result of industrial restructuring and delays in post-pandemic recovery.

The year **2023** appears as a **turning point**, with the **highest total number of compensated unemployed persons** (≈ **110,000 cumulative**, compared to **71,000 in 2021**). This increase can be explained by the expansion of **support programs** and the **re-registration of previously inactive individuals**, a phenomenon also observed at the European level (*European Convention on Human Rights, 2017*).

In the article by *Cruceru & Nijloveanu (2021)*, the dominant trend between **2015–2020** was a **constant decline in unemployment**, with peaks of **9–10% in Oltenia** and lows of **1–2% in the West**. By contrast, during **2020–2024**, not only do **regional disparities persist**, but **long-term unemployment** increasingly concentrates among individuals **over 40 years old**, indicating a gradual **aging of the active labor force**.

Partial conclusions

1. **Women and individuals over 40 years old** are more exposed to the risk of long-term unemployment.
2. The year **2023** marked a **temporary rise** in both total unemployment and the **average job-seeking duration**.
3. **Vocational training programs** implemented after 2021 reduced unemployment duration among **young people**, but the impact on the **40+ age group** remains limited.
4. The results confirm the **need for differentiated policies by age and gender** to address labor market segmentation and social exclusion.

d) Structure of unemployment by education level

Table 2

Registered unemployed beneficiaries of unemployment benefits, by education level

(NIS, http://statistici.insse.ro)

Age groups	Genders	Categories of unemployed people by education level	2020	2021	2022	2023	2024
			U.M.: Number of persons				
Overall	Overall	Primary, secondary, and professional	47,942	29,563	22,652	26,369	28,581
		High school and post-secondary education	40,652	23,359	17,814	20,313	22,491
		University	12,146	6729	5065	5734	7052
	Female	Primary, secondary, and professional	25,871	14,222	10,913	13,291	15,155
		High school and post-secondary education	25,756	14,545	11,365	12,903	14,590
		University	7756	4311	3423	3835	4693
Under 25 years old	Overall	Primary, secondary, and professional	2537	1502	1469	1511	1133
		High school and post-secondary education	8121	4905	3890	4276	4372
		University	940	476	423	487	572
	Female	Primary, secondary, and professional	1224	650	655	640	447
		High school and post-secondary education	4422	2708	2141	2330	2367
		University	638	334	314	342	388
Aged 25-29 years old	Overall	Primary, secondary, and professional	1379	468	330	362	363
		High school and post-secondary education	2330	891	823	925	940
		University	1133	414	380	419	493

	Female	Primary, secondary, and professional	761	260	151	174	193
		High school and post-secondary education	1509	535	566	553	607
		University	751	277	250	281	340
Aged 30-39	Overall	Primary, secondary, and professional	7067	3257	2509	2843	2839
		High school and post-secondary education	6225	2970	2564	2829	3206
		University	3756	1740	1443	1561	1816
	Female	Primary, secondary, and professional	4015	1723	1278	1472	1561
		High school and post-secondary education	4244	1997	1793	1836	2146
		University	2656	1265	1119	1158	1356
Aged 40-49	Overall	Primary, secondary, and professional	15,394	9069	6682	7542	7930
		High school and post-secondary education	10,156	5244	3880	4293	4729
		University	3330	2013	1473	1686	2090
	Female	Primary, secondary, and professional	8644	4530	3366	3933	4410
		High school and post-secondary education	7017	3549	2646	2944	3312
		University	2135	1314	985	1136	1381
Aged 50-55 years	Overall	Primary, secondary, and professional	12,652	8850	6443	7297	7601
		High school and post-secondary education	8701	5715	3884	4281	4511
		University	1878	1260	812	827	966
	Female	Primary, secondary, and professional	7118	4424	3246	3864	4178
		High school and post-secondary education	5914	3776	2630	2976	3189
		University	1165	807	515	562	631
Over 55 years old	Overall	Primary, secondary, and professional	8913	6417	5219	6814	8715
		High school and post-secondary education	5119	3634	2773	3709	4733
		University	1109	826	534	754	1115
	Female	Primary, secondary, and professional	4109	2635	2217	3208	4366
		High school and post-secondary education	2650	1980	1589	2264	2969
		University	411	314	240	356	597

The statistical data provided by the **National Institute of Statistics (INS)** reveal a clear relationship between the **level of education and the risk of unemployment**. During the period **2020–2024**, individuals with **primary, secondary, or vocational education** represented the most vulnerable category in the labor market.

- In **2024**, nearly **29,000 persons** with primary, secondary, or vocational education were registered as unemployed, compared to approximately **7,000 persons** with university degrees.
- This distribution indicates that **lower educational attainment is strongly associated with a higher risk of unemployment**, a finding consistent with the observation published by *HotNews (2025)*.
- The *ANOFM Report (2024)* also emphasizes the need to **guide individuals with low or no formal education toward vocational training and retraining programs**, in order to improve their employability and integration into the labor market.

e) Participation in vocational training courses (Romania, 2020–2024, U.M. = Number of persons)

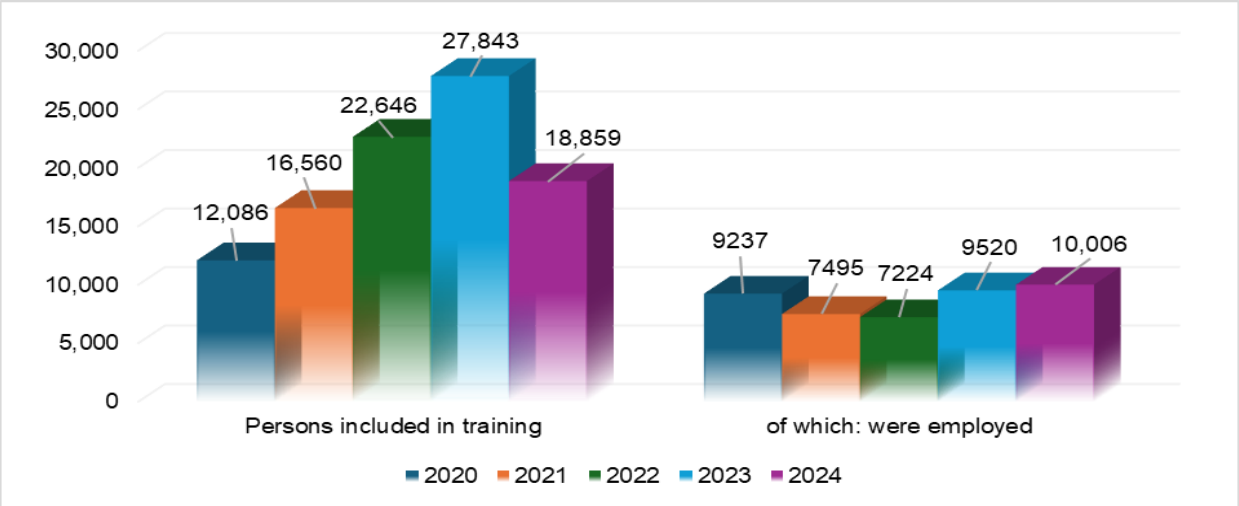

Fig. 3 - Persons enrolled in vocational training courses
(NIS, http://statistici.insse.ro)

Data from the **National Institute of Statistics (INS)** show a significant **increase in participation in vocational training courses between 2020 and 2023**, peaking at nearly **28,000 participants in 2023**. However, in **2024**, participation decreased by approximately **32%**, suggesting that **post-pandemic retraining programs either ended or experienced reduced funding**.

According to the **National Employment Agency (ANOFM)**, in **2023** a total of **934 vocational training courses** were organized, with **over 11,000 participants**, of whom **more than 70% were women** and **60% were aged over 30** (*Cosmin Meca, 2025*).

For example, the **Dolj County Employment Agency (AJOFM Dolj)** informs unemployed individuals about available employment support programs and incentives, offering **counseling, mediation, and professional training services**, as well as a **monthly financial supplement of 30% of the unemployment benefit** for those employed full-time.

These figures confirm a **direct correlation between active labor market measures and the temporary reduction in unemployment during 2021–2023** (*ANOFM, 2024*).

1. **Increase in access to vocational training after 2020**
   - In the **post-pandemic context**, the **ANOFM** and the **Ministry of Labor** launched retraining programs funded by the **European Social Fund**, targeting sectors such as **services, agriculture, and construction**.
   - **Employment rate of course participants**
   - During **2020–2022**, only about **one-third** of course graduates found employment within six months.
   - After **2023**, the share of employed participants increased significantly, exceeding **50%** (**10,006 employed persons out of 18,859 participants in 2024**).
   - **Educational profile of participants**
   - The majority of those enrolled in training had **vocational or secondary education**, consistent with the overall structure of the unemployed population (*SOM101C data*).
   - The **ANOFM** specifies that the main qualifications targeted were in the fields of **retail work, computer operation, electrical work, welding, and cooking**.
   - The proportion of participants with **higher education** remained below **10%**, indicating a **pragmatic focus on practical, labor-intensive occupations** with high market demand. **Partial conclusions**
2. **Participation in vocational training programs** increased significantly between **2020 and 2023**, reaching the highest level of the decade.
3. The **post-training employment rate** improved but remains **region- and sector-dependent**.
4. Most participants come from **vocational and secondary education backgrounds**, confirming the relevance of training for this category.
5. There remains a need for **stronger alignment between vocational training and real labor market demand**, as emphasized by both the **INS** and **ANOFM**.
6. From a **regional perspective**, retraining programs should be **expanded in the South-West Oltenia and North-East regions**, where unemployment remains the highest.

S.W.O.T. analysis

Following the statistical interpretation presented above, the S.W.O.T. analysis aims to synthesize the main strengths, weaknesses, opportunities, and threats that define the Romanian labor market during the 2020–2024 period. This strategic approach allows for the integration of quantitative data provided by the National Institute of Statistics (INS) and the National Employment Agency (ANOFM) into a conceptual framework that explains not only what happened, but also why it happened.

By correlating **regional, educational, and occupational dimensions**, the S.W.O.T. analysis provides a coherent overview of the **structural dynamics of unemployment in Romania**, highlighting:

- the **internal factors** that support or limit labor market performance;
- the **external opportunities** generated by economic, technological, and demographic changes;
- the **risks** that may amplify regional and social imbalances.

This synthesis serves as the **logical foundation** for the conclusions and recommendations presented in the next section, which aim to identify **priority directions for action** to increase employment levels and reduce structural vulnerabilities.

Table 3

Labor Market and Unemployment in Romania (2020–2024)

(Source: Own determination.)

Category	Summary analysis
Strengths	The overall unemployment rate remained at a low level (2–4%), among the lowest in the European Union, according to data from INS and Eurostat. Increased participation in vocational training programs, reaching a peak in 2023 with more than 27,000 participants. Gradual reintegration of young people into the labor market after the COVID-19 pandemic, supported by ANOFM programs. Rising employment rates among training graduates, particularly among individuals with secondary education. The West, North-West, and Bucharest–Ilfov regions recorded remarkable economic stability and a high capacity for labor market absorption.
Weaknesses	Persistent regional disparities – a 5.5 percentage point gap between the regions with the lowest and highest unemployment rates (Bucharest–Ilfov vs. South-West Oltenia). High proportion of unemployed individuals with primary or vocational education (over 50% of the total). Major reintegration challenges for individuals over 45 years old, particularly women. Decreased funding and declining interest in vocational training programs in 2024 (–32% compared to 2023).
Opportunities	Expansion of retraining programs financed through European Union funds (2021–2027). Digitalization of ANOFM services and the potential for rapid career reconversion in emerging sectors such as IT, green services, and renewable energy. Growing interest in technical qualifications and high-demand trades — including electricians, installers, computer operators, and retail workers — reflecting a stronger alignment between vocational education and labor market needs.
Threats	Aging of the active labor force – a continuous decline of over 100,000 employable individuals per year. Ongoing migration of skilled young workers toward EU countries, particularly affecting the North-East and South-West regions. Accelerated automation of industrial processes, leading to a reduced demand for low-skilled labor. Slow economic growth and geopolitical uncertainty (e.g., the war in Ukraine) negatively impacting private investment. Persistent territorial imbalances that may limit the effectiveness of active employment measures.

The S.W.O.T. analysis confirms several key findings derived from the National Institute of Statistics (INS) data:

- The **Romanian labor force** is **dynamic but segmented**, showing strong performance in the **western regions** while **persistent imbalances** remain in the **southern and eastern areas**.
- **Education remains the key** to reducing **structural unemployment**, yet the **adaptation of curricula and vocational training** to real labor market needs continues to be **slow and uneven**.
- **Vocational training programs** have produced **visible results only when correlated** with the **local labor market needs** and regional economic context.
- The **low national unemployment rate** does not uniformly reflect reality: in certain counties (**Dolj, Vaslui, Mehedinți**), unemployment **exceeds twice the national average**.

CONCLUSIONS

The analysis of unemployment trends in Romania during the 2020–2024 period reveals an apparent stability of global indicators, yet persistent structural and regional disparities. Based on the statistical data provided by the National Institute of Statistics (INS) and reports from ANOFM, the following conclusions can be formulated:

1. The **overall unemployment rate** remained **low (2–4%)**, placing Romania among the **European countries with the lowest unemployment levels**. However, this performance conceals **deep divides** between the **western regions** and the **south-eastern ones**, where unemployment remains **two to three times higher**.

2. The **structure of unemployment** is strongly influenced by the **educational level**. Individuals with **primary or vocational education** continue to represent the most vulnerable category (over **50%** of the total), while **university graduates** display a **significantly higher probability of reemployment** (*HotNews, 2025; ANOFM, 2024*).
3. The **age and gender distribution** confirms a **segmented labor market**. **Women and individuals over 40** are more exposed to **long-term unemployment**, while **young people under 25** face **short-term but volatile unemployment**. These trends reflect both **qualification gaps** and **differences in professional adaptability** (*Cruceru and Nijloveanu, 2021*).
4. **Vocational training programs** had a **positive impact**, particularly between **2021–2023**, when participation increased by over **100%**. However, in **2024**, participation declined by **32%**, suggesting the **need for continuity and updated training curricula** (*Cosmin Meca, 2025; ANOFM, 2024*).
5. The **S.W.O.T. analysis** confirms the existence of a **dynamic yet structurally imbalanced labor market**. The **strengths**, such as low unemployment rates and increased participation in vocational programs, coexist with major **weaknesses** — regional economic dependence, poor alignment between education and labor demand, and the **aging of the active workforce**.
6. **Future perspectives** for the post-2024 period depend on **strengthening training and retraining policies**, **reducing regional disparities**, and **aligning the educational system** with the requirements of the **digital and green economy**. Without an integrated approach, the risk of **social and territorial polarization** will intensify.

In conclusion, **Romania stands at a fragile equilibrium** between **macroeconomic performance** and **structural vulnerabilities** within its labor market. The progress achieved between **2020–2024** demonstrates a **strong adaptive potential**, but also highlights the **need for coherent employment policies** oriented simultaneously toward **education, innovation, and social inclusion**.

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EVALUATION OF PLANTS AND AGRICULTURAL TECHNOLOGIES USED FOR SOIL CARBON SEQUESTRATION WITHIN SUSTAINABLE AGRICULTURAL SYSTEMS

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EVALUAREA PLANTELOR ȘI TEHNOLOGIILOR AGRICOLE UTILIZATE PENTRU SECHESTRAREA CARBONULUI IN SOL ÎN CADRUL SISTEMELOR AGRICOLE DURABILE

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ABSTRACT

Soil carbon sequestration is one of the most effective natural strategies for climate change mitigation. This article reviews the main plant groups and agricultural technologies involved in soil carbon capture and storage, with a focus on perennial species, legumes and agroforestry systems. Synthetic data on the sequestration potential expressed in t CO_2/ha/year are presented, as well as the contribution of modern technologies such as no-till, cover crops and the use of biochar. The results highlight the importance of combining vegetation management with regenerative practices to increase organic carbon content and improve soil fertility.

REZUMAT

Sechestrarea carbonului în sol reprezintă una dintre cele mai eficiente strategii naturale de atenuare a schimbărilor climatice. Articolul de față analizează principalele grupe de plante și tehnologii agricole implicate în captarea și stocarea carbonului în sol, cu accent pe speciile perene, leguminoase și sistemele agroforestiere. Sunt prezentate date sintetice privind potențialul de sechestrare exprimat în t CO_2/ha/an, precum și contribuția tehnologiilor moderne precum no-till, culturile de acoperire și utilizarea biocharului. Rezultatele evidențiază importanța combinării managementului vegetației cu practici regenerative pentru creșterea conținutului de carbon organic și îmbunătățirea fertilității solului.

INTRODUCTION

Climate change is one of the greatest global challenges of the 21st century, affecting ecosystems, economies and food security worldwide. The increase in atmospheric concentrations of carbon dioxide (CO_2) is the main factor in the intensification of climate change, in particular due to the accelerated rate of accumulation of greenhouse gases in the atmosphere (*Rodrigues et al, 2023*, *Lorenz and Lal, 2018*). In this context, carbon sequestration in soil stands out as one of the most efficient and sustainable natural solutions, being recognized for its ability to capture and store carbon in the long term, in stable forms that are difficult to re-emit into the atmosphere (*Paustian et al., 2016*).

Agricultural soils function as a major carbon sink, representing approximately two-thirds of the carbon stored in terrestrial ecosystems. They have the capacity to retain significant amounts of organic carbon through biological, physical and chemical processes, such as the accumulation of organic matter, the stabilization of carbon in mineral aggregates and the transformation of organic compounds through microbial activity (*Smith et al., 2012)*.

Globally, agricultural soils store approximately 2,300 gigatons of carbon, exceeding the amount of carbon in the atmosphere and vegetation, which gives them a key role in climate stability (*Batjes et al., 2020*). Proper soil management enhances these natural processes, contributing to the reduction of atmospheric CO_2 and improving soil fertility.

Plants, especially perennial species, legumes and vegetation used in agroforestry systems, play a fundamental role in capturing atmospheric CO_2 through the process of photosynthesis and transferring it to the soil. Perennial species, characterized by a deep and persistent root system, favor the accumulation of

carbon in the lower soil profiles, where it becomes more stable and less susceptible to being re-emitted to the atmosphere (*Gautam et al., 2025; To et al., 2010; Mühlbachová et al., 2025*). Legumes contribute not only to carbon sequestration, but also to improving fertility through biological nitrogen fixation, which stimulates microbiological activity and the formation of stable humus (*Srivastava et al., 2025*; *Rani et al., 2019; Tomić et al., 2023*). Agroforestry systems, which combine trees with agricultural crops or pastures, provide dual storage, both in biomass and in soil, generating some of the highest sequestration rates reported in the literature (*Nair et al., 2009; Abebaw et al., 2025; Tahir A., 2025*).

In parallel, modern agricultural technologies play a crucial role in maximizing carbon storage capacity. Conservative farming practices, such as no-till and minimum-till, reduce the mineralization of organic matter and limit carbon losses through oxidation, favoring accumulation in the upper layers of the soil (*Pittelkow et al., 2015*). Cover crops contribute to increasing carbon supply through root biomass and protect the soil against erosion, facilitating the formation of stable aggregates (*Blanco-Canqui et al., 2015*). Additionally, applying biochar, a carbonized material obtained through the pyrolysis of biomass, improves cation exchange capacity, stabilizes carbon in the long term, and increases the soil's potential to retain additional carbon *(Lehmann et al., 2015)*.

Integrating correct management of plant residues maintains a constant supply of organic matter, intensifying rhizosphere processes and contributing to the formation of persistent humic fractions in the soil.

The increase in atmospheric carbon dioxide (CO_2) concentration is one of the main factors accelerating global climate change, influencing average temperatures, precipitation patterns and the stability of natural and agricultural ecosystems (*Friedlingstein et al., 2019*).

The agricultural sector, although responsible for part of anthropogenic emissions, also has considerable potential for capturing and storing carbon through natural processes, transforming the soil into a reservoir capable of reducing the pressure of greenhouse gases at the atmospheric level (*Smith et al., 2020*). Globally, agricultural soils contain approximately 2,300 gigatonnes of carbon, an amount that exceeds the carbon stored in vegetation and the atmosphere combined, highlighting their strategic role in mitigating climate change (*Batjes et al., 2020)*.

Soil carbon sequestration is a complex process, influenced by the interaction between vegetation, soil and agricultural management. Vegetation type directly determines the carbon supply through aboveground biomass and, especially, through root biomass.

Perennial species, due to their deep roots and longevity, can transfer significant amounts of carbon to the lower soil layers, where it becomes more stable and less susceptible to oxidation (*Gherardi et al., 2020*). Legumes, with a structure rich in protein compounds and with increased nitrogen supply through biological fixation, stimulate the activity of soil microbiota, favoring the transformation of carbon into stable humic forms (*Jian et al., 2020*). Agroforestry systems, which combine trees with agricultural crops or pastures, exhibit some of the highest sequestration rates due to the simultaneous contribution of woody biomass and complex root systems (*Nair et al., 2009).*

In terms of agricultural practices, modern technologies play a significant role in increasing the efficiency of carbon storage processes. Conservation agriculture, by reducing soil tillage, limits the oxidation of organic matter and favors the accumulation of carbon in the upper horizons *(Pittelkow et al., 2015).* Biochar, applied in doses adapted to the soil type, improves cation exchange capacity, stabilizes carbon in the long term and reduces nutrient losses, which contributes to a net increase in organic carbon (*Lehmann et al., 2015)*. Cover crops also provide a constant supply of organic materials and protect the soil against erosion, increasing aggregate stability and reducing carbon mineralization (*Blanco-Canqui et al., 2015*).

In the last decade, research has increasingly focused on identifying plant species with high sequestration potential, as well as on developing sustainable agricultural technologies that maintain the balance between the productivity of agricultural systems and environmental protection (*Smith et al., 2020*).

In this context, perennials, legumes, cover crops and agroforestry systems, together with modern practices such as conservation agriculture or biochar application, have been identified as essential solutions for increasing the capacity of soils to store carbon.

The aim of the paper was to analyze the main categories of plants and agricultural technologies used in carbon sequestration, highlighting the mechanisms through which they contribute to increasing the organic carbon content in the soil and improving its quality.

MATERIALS AND METHODS

The methodology of this study is based on a comparative analysis of data from international scientific sources (FAO, IPCC and European Soil Data Centre), targeting carbon sequestration rates for the main categories of plants and agricultural technologies.

2.1. Types of vegetation analyzed

The analysis of vegetation types aimed to identify plant groups with high carbon sequestration potential, given the significant differences between perennial species, legumes, agroforestry systems and cover crops. Each plant category contributes distinctly to the accumulation of organic carbon in the soil, through specific mechanisms related to root biomass, life cycle, nitrogen fixation capacity and influence on soil structure.

Perennial species, such as perennial grasses and energy crops, are characterized by deep and persistent root systems, capable of transferring carbon to the lower layers of the soil, where it is more stable and less susceptible to degradation. These plants generate a constant accumulation of organic residues and exhibit a high rate of carbon storage due to their longevity and resilience *(Agostini et al., 2015; Gherardi et al., 2020; Gautam et al., 2025).*

Perennial energy crops, including high-yielding herbaceous grasses such as *Miscanthus* spp., *Panicum virgatum* and *Arundo donax*, as well as short-rotation woody crops (willow and poplar), represent systems of great interest for carbon sequestration due to their ability to produce abundant biomass and develop extensive root systems (*Zimmermann et al., 2014*). These systems are characterized by long-term land occupation, 1–15-year cropping cycles and minimal soil disturbance, factors that favor the accumulation of stable organic carbon.

Soil carbon input comes from both aboveground residues and belowground biomass, but in the case of perennial crops, roots are the dominant source of carbon due to their longevity and low decomposition rates *(Rasse et al., 2005*). *Miscanthus* and *Panicum virgatum* have dense root systems in the 0–30 cm layer, contributing substantially to the enrichment of organic carbon reserves, even though their aerial residues have a rapid rotation (*Anderson-Teixeira et al., 2009)*. In woody systems, such as those based on willow and poplar, additional contributions come from dead wood, remaining stumps and coarse roots, with long-term effects on carbon stability (*Pacaldo et al., 2014*).

Compared to conventional systems, perennial energy crops cause higher increases in organic carbon due to reduced soil disturbance, continuous litter input and constant rhizosphere deposition (*Don et al., 2011*). *Miscanthus* is considered one of the most efficient species in sequestering carbon per unit input due to the slow decomposition of residues and the high proportion of root biomass (*Clifton-Brown et al., 2007*). On the other hand, *Panicum virgatum* (switchgrass) exhibits superior adaptability in dry areas, contributing significantly to the organic carbon content in lower quality soils (*Agostini et al., 2015*).

In the case of woody crops (willow and poplar), high growth rates, genetic variability and adaptability to different climates lead to substantial carbon accumulations, both in aboveground biomass and in the soil (*Agostini et al., 2015*). Carbon inputs depend on the amount of litter, root longevity, root system depth and decomposition rates, influenced by temperature, precipitation and soil texture.

Therefore, perennial energy crops are an essential component in the evaluation of carbon sequestration technologies, as they provide stable carbon fluxes to the soil, contribute to the reduction of net greenhouse gas emissions and have a high potential for carbon stabilization in deep soil profiles.

Annual and perennial legumes contribute to improving soil fertility by biological nitrogen fixation, a process that stimulates microbiological activity and the formation of stable humus. Through the combination of nitrogen supply and considerable root biomass, legumes can increase organic carbon content and accelerate carbon stabilization processes in soil aggregates (*Kumar et al., 2018; Jian et al., 2020; Srivastava et al., 2025*).

In the analysis of the efficiency of plant species, legumes occupy a central place due to the significant contribution of root biomass to the accumulation of organic carbon in the soil. Legume roots represent the most stable source of carbon, since belowground biomass and root exudates are directly incorporated into the soil organic matter, having a longer persistence time compared to aerial residues (*Sainju, 2016*). Studies show that the extension of the root system is strongly correlated with the distribution of organic carbon in the deep soil profiles, especially due to the slow decomposition of roots and the stability of carbon from rhizosphere deposition (*Rasse et al., 2005*).

Legume-based rotations promote carbon accumulation at different depths, depending on the type and depth of the root system. Long-term experiments have shown that legume rotations can increase total

soil carbon stocks by over 20 Mg ha^{-1} compared to monoculture, mainly due to the increase in stable carbon in the lower horizons (*Meena et al., 2017*). Carbon deposited under the till layer shows a more biologically resistant character, associated with a higher proportion of aromatic compounds, which supports the role of legumes in long-term carbon sequestration (*Nair et al., 2015*).

Another important mechanism is rhizo-deposition, a process by which legumes release soluble organic compounds, organic acids, amino acids, polysaccharides, mucilage's and secondary metabolites into the soil, which stimulate microbial activity, leading to the formation of stable aggregates and an increase in microbial carbon. The enhanced microbial activity in the rhizosphere zone of legumes favors the carbon cycle, and the death and turnover of roots additionally contribute to the accumulation of carbon in the soil (*Kumar et al., 2018).*

Therefore, legumes, due to their developed root systems, nitrogen fixation capacity and complex rhizosphere dynamics, represent an essential plant category in methodologies for assessing the potential for carbon sequestration in soil, especially in sustainable agricultural rotations.

Agroforestry systems*,* implemented in mixed farms or perennial plantations, combine trees with agricultural crops or pastures, ensuring a continuous flow of carbon through both woody biomass and complex root systems. The presence of trees determines high rates of sequestration due to the accumulation of carbon in wood, foliage and rhizosphere, which makes agroforestry considered one of the most efficient plant strategies for carbon storage *(Nair et al., 2009; Abebaw et al., 2025).*

To assess the contribution of fast-growing agroforestry species to carbon sequestration, root system architecture was analyzed over a three-year period (2017–2019) during the winter season in (*Gautam et al., 2025*). Each year, three healthy and uniform trees of each species were selected: *Neolamarckia cadamba* (kadam), *Leucaena leucocephala* (subabul), and *Melia dubia* (malabar neem), in total nine specimens/species. The trees were uprooted manually and the root structure was exposed by hydraulic fracturing, a method that allows complete visualization of the roots down to relevant depths (*Czernin et al., 2005; Phillips et al., 2014)*.

Aboveground parameters (height, diameter at collar, DBH, crown width) were measured before uprooting. Root parameters assessed included root symmetry and distribution, root depth and extent, root length and diameter per order, branching angles, and root biomass (*Czernin et al., 2005; Marden et al., 2018*). Fine roots (<1 mm) were recorded separately due to their major role in carbon storage.

Root and aboveground biomass were dried at 70 ± 2°C to constant weight (*Peng et Dang, 2003*). Carbon stock was estimated using the (*IPCC, 2006*) formula: *Carbon = dry biomass × 0.5*, and the CO_2 mitigation potential was calculated with a factor of 3.67.

Cover crops, such as rye-clover or oat-pea mixtures, play an essential role in maintaining the continuity of carbon flow in agricultural systems. By providing high root biomass, protecting against erosion and reducing carbon mineralization, cover crops contribute to improving soil structure and stabilizing carbon in organo-mineral aggregates (*Blanco-Canqui et al., 2015)*.

Cover crops contribute to increasing soil organic carbon content by providing additional biomass both above and below ground, particularly through roots, which are a central element in carbon storage (*Blanco-Canqui et al., 2013*). They influence both carbon accumulation and loss processes, reducing soil erosion, one of the main pathways of organic carbon loss, and contributing to soil carbon retention.

Effective cover crops against erosion are those that: produce high biomass (e.g. winter rye, triticale, annual grasses, summer crops); provide dense soil cover during vulnerable periods (spring); have abundant root systems, capable of stabilizing soil aggregates, increasing water infiltration and reducing particle detachment; increase aggregate stability by increasing organic carbon, thus reducing soil erosion (*Blanco-Canqui et al., 2015).*

Cover crops useful for reducing compaction include: species with large taproots (e.g. radish, turnip, rapeseed), capable of creating vertical channels and penetrating compacted layers; species with high root biomass, which reduce soil density and increase organic carbon, improving its structure; mixtures with Brassicaceae, which can be grown alone or in multiple mixtures, contributing to "bio-boring" and reducing compaction. To optimize nutrients, cover crops should: include legumes, which fix atmospheric nitrogen and provide part of the N requirement for subsequent crops; include non-legume species (e.g. grasses), which absorb residual nitrogen and reduce leaching; create both abundant aboveground and belowground biomass, contributing to increasing organic carbon; recycle nutrients from deep soil layers, reducing losses (*Blanco-Canqui et al., 2015)*.

Cover crops can provide additional benefits, such as: weed suppression, through competition and release of allelopathic compounds; creation of a habitat for biodiversity and fauna, providing cover and trophic resources; grazing and forage, in the case of species with high biomass; increasing or maintaining the production of main crops; controlling diseases and pests, by interrupting their biological cycles in diversified rotations (*Blanco-Canqui et al., 2015*). At the same time, the efficiency of cover crops depends on several factors: duration of use (*Acuna & Villamil, 2014*), soil texture (*Berhe et al., 2007*), residue composition (*Fae et al., 2009*), soil tillage system (rapid effect in no-till), (*Olson et al., 2014*), climate (*Blanco-Canqui et al., 2013*).

2.2. Agricultural technologies and practices evaluated

The assessment of the potential for soil carbon sequestration included the comparative analysis of the main agricultural technologies used in sustainable production systems. These practices influence both carbon inputs (aboveground and belowground biomass) and the processes of stabilization of organic matter in the soil, having a direct impact on the variation of total organic carbon.

2.2.1. Conservative agriculture (no-till și minimum-till)

Reduced tillage systems, especially no-till, limit physical soil disturbance, reduce accelerated organic matter mineralization, and promote carbon accumulation in the upper horizons (*Pittelkow et al., 2015*). By maintaining residues on the surface and reducing organic carbon oxidation, conservation agriculture increases aggregate stability and promotes the formation of durable soil–organic matter structures (*Six et al., 2002*). No-till also improves water infiltration and reduces erosion, decreasing carbon losses associated with soil transport.

2.2.2. Biochar application

Biochar, a carbonized material obtained by pyrolysis of biomass, is one of the most effective practices for carbon stabilization on a decadal or secular scale. Application rates ranging from 5–20 t/ha improve organic carbon stocks by increasing the stable fraction, reduce the decomposition of native organic matter, and improve the physicochemical properties of the soil (*Lehmann & Joseph, 2015*). Its aromatic structure confers high resistance to mineralization, and its high porosity supports beneficial microbial activity and nutrient retention.

2.2.3. Improved crop residue management

Retention of residues on the soil, their chopping and uniform distribution increase the carbon supply through a constant flow of biomass readily available for microbial processes (*Lal, 2005*). This type of management reduces erosion losses, promotes rhizosphere activity and contributes to the formation of stable humus. Residues rich in lignin and high C/N ratio slow down decomposition, favoring the accumulation of organic carbon in the soil in the long term.

2.2.4. Crop rotation and diversification of production systems

Diversified rotations, including legumes, perennial crops, or deep-rooted crops, increase soil carbon flux and reduce carbon loss through long periods without vegetation (*West & Post, 2002*). The introduction of crops with complementary root systems improves the distribution of carbon throughout the soil profile and supports complex microbial activity. Crop diversification also reduces the need for tillage, facilitating a more favorable balance for carbon sequestration.

2.2.5. Mixed agroforestry and silvopastoral systems

Agroforestry systems, as well as silvopastoral systems, combine trees with crops or pastures, providing a dual mechanism for carbon accumulation: in woody biomass and in soil (*Nair et al., 2009*). The deep roots of trees contribute to carbon sequestration at depths inaccessible to annual crops, which favors the formation of stable carbon. Also, interactions between trees, herbaceous plants and microorganisms generate a complex soil–biomass structure, capable of supporting large reserves of organic carbon.

2.3. Indicators used

The assessment of the potential for carbon sequestration in soil was carried out by analyzing a set of quantitative indicators recognized in the specialized literature. These indicators allow the comparison of different types of vegetation and agricultural practices according to their capacity to capture and stabilize carbon at the soil level.

In order to comparatively evaluate the efficiency of different plants and agricultural technologies in carbon sequestration, four main indicators, internationally recognized in soil carbon monitoring analyses, were used. These indicators allow the quantification of annual carbon fluxes, the determination of total organic carbon variations, the assessment of carbon stability in organo-mineral fractions and the estimation of soil fertility changes in relation to biochemical and microbial processes.

2.3.1. Annual carbon sequestration rate (t CO_2/ha/year)

This indicator represents the annual amount of atmospheric CO_2 transferred and stored in the soil as organic carbon. Its value depends on the input of aboveground and belowground biomass, soil management, and the capacity of the ecosystem to stabilize carbon in recalcitrant forms (*Paustian et al., 2016*). In meta-analysis studies, sequestration rates range from 0.1 to 3 t CO_2/ha/year depending on crop, species, climate, and agricultural technology used (*Smith et al., 2020*).

2.3.2. Soil organic carbon content (SOC, %)

SOC (%) is the central indicator of soil quality and carbon sequestration efficiency. SOC variations are measured at different depths (0–15, 0–30 or 0–60 cm), because carbon distribution is strongly influenced by vegetation type and rhizosphere activity (*Lal, 2005).* SOC increases reflect the accumulation of stable organic matter, but also the improvement of soil structure, water retention and microbial biodiversity.

2.3.3. Carbon stability in organo-mineral fractions

To assess the sustainability of sequestration, carbon is analyzed according to its fractions: particulate carbon (POM), mineral-associated carbon (MAOM) and humified carbon. Mineral-associated carbon is the most stable form, with a residence time of tens to hundreds of years (*Cotrufo et al., 2013*). Physical and chemical fractionation techniques allow the estimation of the proportion of stabilized carbon, providing essential information on the vulnerability of SOC to disturbances (*Yadav et al., 2025*).

2.3.4. Evolution of soil fertility (N, P, K, C/N ratio)

Changes in nitrogen (N), phosphorus (P), potassium (K) and C/N ratios are monitored to characterize the impact of agricultural technologies on soil ecosystem functioning. Legumes increase nitrogen availability through biological fixation, perennial crops stimulate nutrient cycling through root deposition, and biochar improves cation exchange capacity and macronutrient retention (*Lehmann & Joseph, 2015*). The C/N ratio is an indicator of organic matter stability and mineralization rate, influencing both carbon sequestration and crop productivity.

A synthesis of these indicators is presented in table 1.

Table 1

Indicators used to assess the potential for carbon sequestration in soil

Indicator	What it measures	Relevance for sequestration	Bibliography
Annual carbon sequestration rate (t CO_2/ha/year)	Amount of atmospheric CO_2 stored annually in soil	Estimates the net efficiency of the agricultural system in carbon capture	*(Paustian et al., 2016*)
Soil organic carbon content (SOC, %)	Percentage of organic carbon accumulated in different horizons	Major indicator of soil quality and long-term carbon accumulation	(*Lal, 2005*)
Stability of carbon in organo-mineral fractions: particulate carbon (POM), mineral-associated carbon (MAOM)	Distribution of carbon between labile and stable forms	Allows assessment of carbon resistance to decomposition and its persistence	*(Cotrufo et al., 2013*)
Evolution of soil fertility (N, P, K, C/N ratio)	Changes in major nutrients and C/N ratio	Reflects the impact of vegetation and technologies on microbial processes and the C–N cycle	(*Lehmann & Joseph, 2015*)

RESULTS

3.1. Comparison of the sequestration potential for the categories analyzed

To assess the efficiency of different types of vegetation and agricultural technologies in the process of carbon sequestration, a comparative synthesis was carried out based on centralized data from the specialized literature.

Table 2 presents the average ranges reported in international studies regarding the annual sequestration rate expressed in t CO_2/ha/year, the biological mechanisms involved and the particularities of each category analyzed.

These results allow a direct comparison between perennials, legumes, cover crops, conservation-agricultural technologies, biochar and agroforestry systems, highlighting the differences between the processes that contribute to the accumulation of organic carbon in the soil.

Table 2

Sequestration potential of the main groups of plants and agricultural technologies

Category	Examples	Carbon sequestration potential *(t CO_2/ha/an)*	Main mechanism	Remarks	Bibliography
Perennials	Miscanthus, Panicum virgatum, Salix, Populus	**2.5 – 6.0**	Deep and persistent root system; accumulation in the 20–60 cm layer	Slowly decomposing residues; rapid SOC growth	(*Anderson et al., 2009); (Don et al. (2011)*
Legumes	Alfalfa, Clover, Pea, Chickpea	**1.2 – 3.0**	Root biomass + biological N fixation, stimulating humification	Stable carbon under the tillage layer; long-lasting effect	(*Nair et al. 2015)*
Cover Crops	Rye–clover, Oat–pea, Veal, Radishes	**0.3 – 1.0**	Constant biomass supply, erosion reduction	Maximum effect in no-till systems	(*Poeplau & Don 2015); (Blanco-Canqui et al., 2013)*
Biochar	Doses 5–20 t/ha	**1.0 – 3.5**	Recalcitrant carbon, persistent >100 years	Increases CEC and aggregate stability	*(Lehmann & Joseph 2015)*
Conservative Agriculture	No-till, minimum-till	**0.4 – 1.5**	Reduced mineralization, accumulation in 0–10 cm	Slow growth; depends on residues and rotation	*(Pittelkow et al., 2015)*
Agroforestry Systems	Acacia with crops, walnut with pasture	**2.0 – 8.0**	Double storage: tree biomass + soil carbon	One of the most effective global strategies	(*Nair et al., 2009); (Abebaw et al., 2025*)

The comparative analysis highlights significant differences between plant categories and agricultural technologies in terms of carbon sequestration potential. Agroforestry systems stand out for their highest values, reaching 2–8 t CO_2/ha/year, due to the double carbon input from both woody biomass and soil. These are followed by perennial species, especially energy crops (*Miscanthus, Panicum virgatum*), which show high sequestration rates due to their deep root systems and slow-decomposing residues.

Legumes, although with a moderate potential (1.2–3.0 t CO_2/ha/year), contribute significantly to carbon stabilization by stimulating microbiological activity and increasing humus content due to biological nitrogen fixation. In contrast, cover crops have lower values (0.3–1.0 t CO_2/ha/year), but play an essential role in reducing erosion and improving soil structure, their cumulative effects being particularly visible in no-till systems.

The application of biochar represents one of the most stable and persistent forms of carbon storage (1.0–3.5 t CO_2/ha/year), with the carbonized material remaining in the soil for centuries. Also, conservation agriculture contributes to reducing carbon losses by limiting soil tillage, but its efficiency strongly depends on the annual supply of crop residues. Overall, the results indicate that integrated strategies, combining perennial vegetation with regenerative technologies such as no-till, biochar or cover crops, offer the highest potential for sequestration and the best stability of soil organic carbon

Most studies show that the use of cover crops causes significant increases in soil organic carbon in the long term. A global meta-analysis based on 37 studies estimated that cover crops can sequester 0.32 ± 0.08 Mg C ha^{-1} yr^{-1} in the 0–22 cm layer (*Poeplau et Don, 2015*). Other research has reported accumulations ranging from 0.10 to 1 Mg C ha^{-1} yr^{-1} when cover crops are integrated into no-till systems (*Blanco-Canqui et al., 2013*). A 12-year study in Illinois showed that *Vicia villosa* and *Secale cereale* caused sequestration: 0.88 Mg C ha^{-1} yr^{-1} in no-till systems, 0.49 Mg under chisel plowing, 0.10 Mg under conventional plowing (*Olson et al., 2014*).

In conclusion, cover crops increase soil organic carbon both at the surface and deep down, especially in no-till systems and in the case of deep-rooted species. However, the magnitude of the effect is strongly dependent on soil, climate and management conditions.

3.2. Analysis of evaluation indicators

The values obtained in the literature analyzed for the ***annual carbon sequestration rate*** highlight significant variations depending on the type of vegetation and the technology applied. Thus, agroforestry systems and perennial energy crops reach the highest values, due to the extensive root systems, plant longevity and high stable biomass input. At the opposite pole, cover crops show low but constant values, with an important cumulative effect over time, especially in no-till systems.

The increase ***in soil organic carbon content*** is determined both by the input of plant residues and root biomass, and by the reduction of losses through mineralization or erosion. Perennial systems, legumes and biochar application demonstrated the greatest increases in SOC, due to slow decomposition, stable input of organic matter and the protective capacity offered by mineral microaggregates. An important aspect is the fact that SOC changes become detectable only after longer periods (3–10 years), being strongly influenced by soil texture, moisture and management.

Regarding ***the stability of carbon in organo-mineral fractions***, stable fractions, such as humus and carbon associated with mineral aggregates, are formed more efficiently in systems with: perennial plants with deep roots; legumes that stimulate microbial activity; biochar with an aromatic structure resistant to decomposition; agroforestry systems that introduce long-lasting lignified carbon. The application of biochar, in particular, contributes to the creation of recalcitrant forms of carbon, with persistence of the order of centuries, representing one of the most efficient strategies for stable storage.

Carbon sequestration cannot be analyzed independently of the ***evolution of soil fertility*** (N, P, K, C/N ratio), because the biological processes involved in SOC accumulation are directly influenced by nutrients. ***Legumes*** **improve nitrogen levels through biological fixation, which stimulates humus formation.** ***Cover crops*** **help maintain phosphorus and potassium in the upper layer, reducing losses through leaching.** ***Conservation agriculture*** **maintains a favorable C/N ratio, due to limiting rapid mineralization.** ***Biochar*** **improves cation exchange capacity (CEC), facilitating nutrient retention and increasing soil fertility in the long term. Overall, regenerative agricultural systems not only increase carbon stocks, but also improve soil quality, which contributes to increased productivity and resilience of agroecosystems.**

3.3. Comparative analysis between systems

Comparative analysis of different vegetation types and agricultural technologies highlights the strong contrast between traditional and regenerative strategies in terms of carbon storage and soil quality improvement. The observed differences reflect both the biological particularities of the species used and the cumulative effects of long-term agricultural management.

3.3.1. Perennial vegetation versus annual vegetation

Systems based on perennial plants, such as *Miscanthus, Panicum virgatum*, willow or poplar, have the highest sequestration capacities, due to: deep and persistent root systems, long duration of land occupation, constant supply of organic residues, high stability of carbon stored in deep horizons. In contrast, annual crops contribute to more modest increases in SOC, as periods without vegetation favor carbon losses through erosion and accelerated mineralization.

3.3.2. Legumes versus cover crops

Legumes have a superior potential to cover crops by: biological nitrogen fixation, stimulation of microbial activity, creation of stable humic fractions. Cover crops, although with lower annual sequestration rates, compensate by: significantly reducing erosion, covering the soil during critical periods, increasing structural aggregation. In no-till systems, the interaction between the two categories becomes synergistic, maximizing long-term SOC accumulation.

3.3.3. Biochar versus waste management

Biochar application offers a major advantage by introducing a recalcitrant form of carbon with stability on the order of centuries, while residue management provides labile carbon, rapidly integrated, but also rapidly mineralized. The key differences are, on the one hand, that *biochar* has a slow but extremely stable SOC growth, while *plant residues* have a fast but volatile growth, requiring constant renewal. Integrating biochar into humus-poor soils and perennial systems produces superior results.

3.3.4. Agroforestry systems versus monocultures

Agroforestry systems are distinguished by the highest carbon sequestration rates due to: simultaneous carbon input from woody biomass and herbaceous crops, complex root extension, improved microclimate and reduced soil temperature, efficient internal nutrient cycling.

In comparison, monocultures, even those managed in a conservative system, have a much lower carbon storage capacity and increased vulnerability to degradation.

3.3.5. Conservative systems versus conventional tillage systems

Conservative farming (no-till, minimum till): reduces rapid humus mineralization, maintains soil aggregates intact, reduces erosion losses and maximizes the effects of cover crops.

In contrast, conventional tillage: accelerates carbon oxidation, reduces organic carbon stability and requires a constant supply of biomass to maintain SOC levels.

The results highlight that maximum efficiency is obtained when conservative systems are integrated with perennial vegetation, legumes or cover crops.

To summarize the results obtained and highlight the functional differences between the analyzed systems, table 3 presents a comparison between the main groups of plants and agricultural technologies from the perspective of sequestration mechanisms, effects on soil organic carbon and stability of stored carbon.

The results confirm that agroforestry systems and perennial energy crops present the highest sequestration potential, due to the continuous supply of biomass and well-developed root systems. Biochar represents a recalcitrant source of carbon, with very long-term stability, while legumes and cover crops contribute through biological and structural mechanisms to the increase of SOC.

Conservation agriculture has a significant potential, but strongly dependent on the annual supply of residues and the integration with other regenerative practices.

Table 3

Comparative synthesis of systems analyzed from the perspective of carbon sequestration

Category / System	Main mechanism of sequestration	Effect on Soil organic carbon content (SOC)	Carbon stability	Other agronomic effect	Overall efficiency
Agroforestry	Double layering (wood + grass), deep roots, stable microclimate	High growth (2–8 t CO_2/ha/year)	Very high due to lignified carbon	Reduces erosion, improves biodiversity	Very high
Perennial energetic (*Miscanthus, Panicum, Salix, Populus*)	Deep roots, stable residues, slow decomposition	High (2–5 t CO_2/ha/year)	High	Protects the soil, requires few inputs	Very high
Legumes	Biological nitrogen fixation, root exudates, microbial stimulation	Moderate (1.2–3 t CO_2/ha/an)	Medium–High	Improve fertility, soil aggregation	High
Cover crops	Root biomass supply, reduce erosion, structural aggregation	Low–moderate (0.3–1 t CO_2/ha/year)	Medium	Protects the soil in the off-season	Medium
Biochar	Recalcitrant aromatic carbon, strong mineral protection	High (1–3.5 t CO_2/ha/year)	Extremely high (centuries persistence)	Increases cation exchange capacity (CEC), retains water and nutrients	Very high
Conservation agriculture (no-till)	Reduction of SOC oxidation, stable aggregates, surface residues	Variable (0.2–1.5 t CO_2/ha/year)	Medium	Reduces fuel consumption, erosion	Medium

The integrated implementation of perennial vegetation, legumes, cover crops and regenerative technologies such as biochar and conservation agriculture represents the most effective natural solution for increasing soil carbon sequestration and strengthening the sustainability of agroecosystems.

CONCLUSIONS

1. Agricultural systems based on perennial vegetation and agroforestry represent the most efficient natural carbon sequestration strategies, due to their deep root systems, high biomass input and stability of lignified carbon in the soil.
2. Legumes play an essential role in the accumulation of organic carbon, through biological nitrogen fixation, stimulation of microbial activity and the formation of stable humic fractions. Their integration into agricultural rotations contributes significantly to the long-term increase in SOC.
3. Cover crops contribute to carbon sequestration mainly by reducing erosion and improving soil structure, their cumulative effects becoming especially evident in conservative (no-till) systems.
4. The application of biochar is one of the most promising technologies for stable carbon storage, due to its recalcitrant nature, which allows a persistence in the soil of the order of centuries. Maximum efficiency is achieved in degraded or organic matter-poor soils.
5. Conservation agriculture contributes to reducing carbon losses through mineralization and erosion, but its effectiveness depends on the annual input of residues and the combination with perennial species or cover crops.
6. The results indicate that the most effective strategies are integrated ones, which combine perennial vegetation, legumes, cover crops and regenerative technologies such as biochar or no-till, thus maximizing soil carbon accumulation while improving the fertility and resilience of agroecosystems.
7. The implementation of these practices in sustainable agricultural systems can contribute substantially to climate change mitigation, by increasing soil organic carbon content and reducing net CO_2 emissions.

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PERFORMANCE EVALUATION OF AN INNOVATIVE EQUIPMENT FOR SOWING GRASS BETWEEN VINE AND FRUIT TREE ROWS

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EVALUAREA PERFORMANȚEI UNUI ECHIPAMENT INOVATIV PENTRU SEMĂNATUL IERBURILOR ÎNTRE RÂNDURILE DE VIȚĂ-DE-VIE ȘI POMI FRUCTIFERI

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ABSTRACT

The paper presents the results obtained in laboratory and field tests on the performance of innovative equipment designed for sowing grass between rows of vines and fruit trees. The analyses focused on the uniformity of seed distribution in the pneumatic system, soil resistance to penetration, soil moisture, and the accuracy of working depth adjustment. The results showed uniform distribution (Cv < 3%) and a low deviation from the technological norm (6.67%), confirming the efficiency of the equipment and its applicability in sustainable agricultural systems.

REZUMAT

Lucrarea prezintă rezultatele obținute în cadrul testelor de laborator și de teren privind performanța unui echipament inovativ destinat semănatului ierburilor între rândurile de viță-de-vie și pomi fructiferi. Analizele efectuate au vizat uniformitatea distribuției semințelor în sistem pneumatic, rezistența solului la penetrare, umiditatea solului și precizia reglajului adâncimii de lucru. Rezultatele au arătat o distribuție uniformă (Cv < 3%) și o abatere redusă față de norma tehnologică (6,67%), confirmând eficiența echipamentului și aplicabilitatea acestuia în sisteme agricole sustenabile.

INTRODUCTION

Modern viticulture and fruit growing systems are undergoing rapid transformation, driven by pressures from climate change, soil depletion, and the need to use chemicals *(Huang J. et. al. 2025)*.

In this context, maintaining row spacing through controlled grassing is one of the most effective and sustainable practices for soil conservation, erosion reduction, and functional biodiversity improvement *(Orzech, K. et. al. 2021).*

Grassing between rows contributes to soil structure stabilization, moisture retention, increased organic matter levels, and reduced compaction, effects that have been documented in numerous recent studies in the international literature *(Zalai M. et. al. 2025).*

In viticulture, ground cover plays an essential role in regulating the soil microclimate, limiting evaporation, and increasing water infiltration capacity, thus contributing to more efficient water management *(Abad, J., et. al., 2021)*.

This practice improves biodiversity, soil activity, and its capacity to store carbon *(Zumkeller, M. et. al. 2023)*. The results obtained in plantations where partial grassing is used indicate a significant reduction in erosion and increased aggregate stability, which are crucial aspects for plots located on sloping land or on soils susceptible to degradation *(López-Vicente, M., et. al. 2020).*

The introduction of ground cover also helps reduce dependence on herbicides, an increasingly important aspect in the context of European regulations on reducing pesticide use. In orchards, the benefits extend to maintaining pollinator biodiversity and biological pest control *(Novara, A., et. al. 2019).*

However, the application of cover crop technologies requires a careful technical approach, as competition for water and nutrients can negatively affect the development of trees or vines in drought conditions *(Silvestroni, O., et. al. 2024).*

To counteract these limitations, it is essential to use high-performance equipment that allows for precise sowing of grasses in narrow intervals, with uniform dosing and strict control over working depth *(Bogunovic I., et. al. 2019)*. Modern pneumatic equipment used in viticultural systems allows for uniform distribution of seed mixtures, ensuring a homogeneous layer of vegetation, even in varied soil conditions *(Novara, A., et. al. 2018)*.

The uniformity of seed distribution is a key parameter, having a direct impact on the stability of the vegetation cover *(Juraj L., et. al. 2024)*, weed control, and the efficient operation of mechanized soil maintenance systems *(Fernandes de Oliveira, et. al. 2021).*

In the specialized literature, numerous studies highlight the importance of developing sowing technologies adapted to perennial crops, ensuring both mechanical performance and operational sustainability *(Trigo-Córdoba, et. al. 2015).* Pneumatic distribution systems, illustrated in Figure 1, are commonly evaluated in terms of distribution uniformity, deviations from the target seeding rate, and their interaction with operating parameters such as metering speed or air velocity in the transport network, as shown in Figure 2.

The evaluation of these parameters becomes crucial for the correct implementation of modern technologies in the field (*Zhu X., et. al. 2024*).

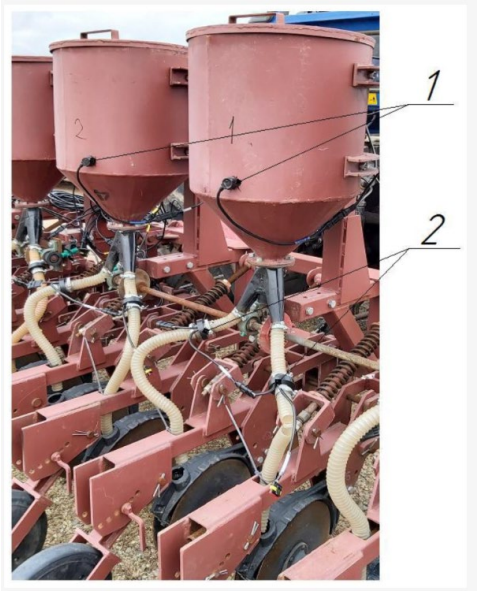

Fig. 1 - The placing of the sensors: 1- sensors for monitoring the level of the bunkers; 2 - sensors for monitoring the sowing of the seed material

(Aduov M., et. al. 2023)

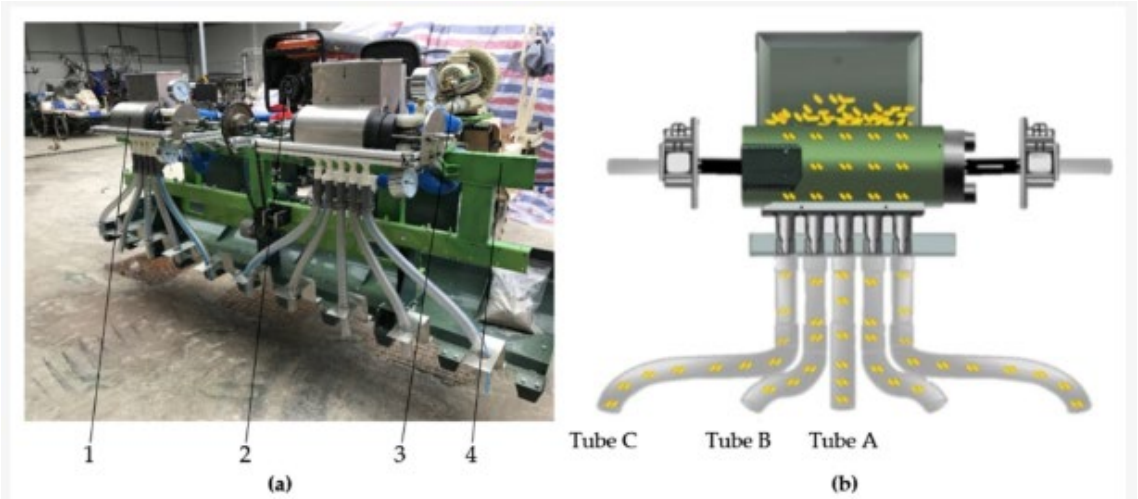

Fig. 2 - The schematic diagram of direct seeder and distributed seed-drop tubes;

(a) main structure of rice-direct seeder. 1. seed metering device 2. gasoline engine 3. centrifugal fan 4. riding rice transplanter head; (b) seed metering device with distributed seed-drop tubes

(Wang B., et. al. 2023)

Although the literature provides valuable insights into the ecological and agronomic effects of grassing, there is still a lack of experimental data on the behavior of machinery under real working conditions, especially in perennial plantations where space is limited and soil conditions are extremely variable. In addition, adapting equipment to the specific requirements of viticulture and fruit growing—such as stability on sloping terrain, dosing accuracy, or uniform distribution in narrow intervals—is a major technical challenge that requires detailed investigation and rigorous testing.

For this very reason, the development of innovative technological solutions capable of integrating the principles of agricultural sustainability with mechanical performance is becoming a strategic objective for the modernization of production systems.

Thus, this paper aims to investigate the performance of innovative sowing equipment designed for vineyards and orchards, analyzing both seed distribution under controlled laboratory conditions and the behavior of the machine in the field. The parameters studied include distribution uniformity, the influence of air speed and dispenser speed, interaction with soil resistance and moisture, and working depth accuracy.

By correlating these data, the paper aims to provide a technical and scientific basis for optimizing grassing technologies and implementing innovative equipment in sustainable agricultural systems.

MATERIALS AND METHODS

The innovative equipment shown in Figure 3 for the pneumatic distribution of grass mixtures between rows of vineyards and orchards ensures uniform seed dispersion over a narrow strip. The system includes a tank with an internal agitator, which maintains a constant flow of seeds to the electronically controlled dispenser. This allows for precise speed adjustment (13.1, 23.3, and 36.6 rpm), influencing the uniformity of distribution.

The seeds are transported by a centrifugal fan and flexible pipes, with compressed air speeds set at 3.95 and 4.46 m/s. The seeds are directed towards inclined deflectors, which ensure uniform spreading on the ground.

In laboratory tests, the machine was equipped with eight independent outlets connected to BOLL-type collection containers. The scale and timer were calibrated to ensure a constant operating time of 30 seconds for each combination of parameters.

The technical setup described allows for controlled tests on distribution uniformity, with the possibility of fine-tuning operational parameters. This facilitates the evaluation of system performance under various conditions, both in the laboratory and in the field.

Fig. 3 - Aspects of preparing innovative equipment for sowing grass between rows of vines and fruit trees for laboratory testing

The experiments used a seed mixture intended for grassing rows in vineyards and orchards, called TERRA FRUCTIS VINIFERA, a NON-GMO variety shown in Figure 4 and containing the following species and proportions: Festuca rubra rubra (30%), Festuca rubra communitata (20%), Festuca arundinacea (30%), and Lolium perenne (20%).

This mix was picked because it can handle different soil conditions, can take repeated cutting, and can grow grass quickly, which are key for keeping a stable plant cover in perennial crops.

The recommended sowing rate for this mixture is 60–80 kg/ha, depending on soil texture and desired coverage intensity.

a b c d

Fig. 4 - Seed used: mixture of Terra fructis vinifera grass for laboratory testing
a) Festuca rubra; b) Festuca rubra communitata; c) Festuca arundinacea; d) Lolium perenne
(https://commons.wikimedia.org/wiki/Category:Festuca_-_botanical_illustrations)

Experimental tests were conducted in the laboratory to determine the uniformity of seed distribution across the eight outlets of the pneumatic system. The experiment was organized according to two variable factors: the speed of the dispenser and the speed of the air supplied by the fan. The experiment analyzed dispenser speeds of 13.1, 13.3, and 36.6 rpm, in combination with air speeds of 3.95 and 4.46 m/s. Each set of parameters was tested in three independent repetitions to ensure the accuracy of the results.

During each repetition, the seeds distributed by each outlet were collected for 30 seconds in BOLL-type containers positioned on a flat surface. The containers were weighed individually on a high-precision laboratory scale, verified prior to testing with standard weights. The operating time was monitored using a calibrated mechanical stopwatch. Air velocity was adjusted using a flow meter and a digital anemometer, calibrated before each series of measurements.

To validate the results obtained in the laboratory, the machine was tested under semi-controlled conditions at two different locations: a vineyard and an orchard. The sowing equipment was attached to a New Holland T50 tractor, and the necessary adjustments were made to set the working depth between 2 and 4 cm, so that the seeds were deposited at an effective depth of 1 to 2 cm, in accordance with technological requirements.

The test area was 60 m long and 1.5 m wide, resulting in a total area of 90 m². During each test, the total mass of seeds consumed by the machine and the working depth achieved were measured. To assess soil conditions, the penetration resistance shown in Figure 5 was determined using a Wile penetrometer, with measurements taken at intervals of 0–10, 10–20, and 20–30 cm depth. Soil moisture, illustrated in Figure 6, was measured using a portable Extech MO750 moisture meter, with each location being evaluated in three replicates.

The results obtained allowed the correlation of the machine's operating parameters with soil resistance and moisture values, in order to identify any influences on sowing uniformity and the actual rate applied in the field.

a b

Fig. 5 - Aspects of measuring penetration resistance with the Wile penetrometer
a) The vineyard; b) The fruit tree plantation

a b

Fig. 6 - Aspects of soil moisture measurement
a) The vineyard; b) The fruit tree plantation

The figures below illustrate aspects captured during semi-controlled field tests conducted with innovative equipment for sowing grass between rows of grapevines (Figure 7) and between rows of fruit trees (Figure 8), respectively.

Fig. 7 - Aspects during semi-controlled (field) testing with innovative equipment for sowing grass between vine rows

Fig. 8 - Aspects during semi-controlled (field) testing of innovative equipment for sowing grass between rows of fruit trees

RESULTS AND DISCUSSION

To assess the uniformity of distribution, the quantity of seeds collected at each outlet was used to calculate the mean, standard deviation, and coefficient of variation (Cv). Values of (Cv) less than 10% were interpreted as indicators of uniform distribution.

The coefficient of variation (Cv) was calculated using the following formula:

$$C_v = \frac{S}{\bar{x}} \times 100 \quad [\%] \tag{1}$$

where: S is the standard deviation,

$$S = \sqrt{\frac{1}{n-1}\sum_{i=1}^{n}(x_i - \bar{x})^2} \quad [g] \tag{2}$$

where: n is the number of distributors;

x_i – the quantity distributed by each distributor;

$\bar{x}$ – absolute mean and is given by the equation

$$\bar{x} = \frac{1}{n}\sum_{i=1}^{n} x_i \quad [g] \tag{3}$$

The average values corresponding to each set of parameters were centralized in a table and subsequently used to compare the degree of uniformity and are presented in Table 1.

Table 1

Speed (rot/min)	Air velocity (m/s)	Media (g)	Standard deviation (g)	Cv (%)	Observation
13,1	3,95	163,4	3,143	1,9	Good uniformity
13,1	4,46	226,600	2,843	1,3	Good uniformity
23,3	3,95	210,467	3,750	1,8	Good uniformity
23,3	4,46	226,6	5,427	2,4	Good uniformity
36,6	3,95	272,9	4,738	1,7	Good uniformity
36,6	4,46	353,033	9,88	2,8	Good uniformity

Table 2 presents data grouped according to air velocity, which allows observation of its influence on the analyzed parameters and comparison of the system's behavior at different velocities.

Table 2

Air velocity (m/s)	C_v (%) at 13,1 rot/min	C_v (%) at 23,3 rot/min	C_v (%) at 36,6 rot/min	C_v average
3,95	1,9	1,8	1,7	1,8
4,46	1,3	2,4	2,8	2,17

Figure 9 shows a graph of the variation coefficients as a function of distributor speed.

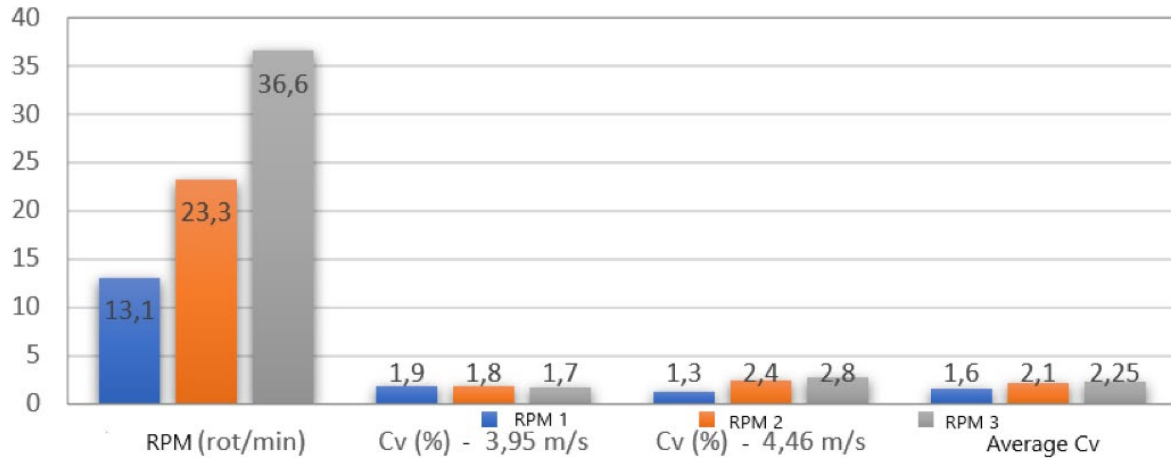

Fig. 9 - Graphical representation of the values of the coefficients of variation as a function of the distributor speed

Analysis of the coefficient of variation (Cv) shows that the stability of the system is higher at low rotational speeds. Thus, at 13.1 rpm, the Cvs are lowest, indicating consistent performance, while increasing speed results in higher Cv values, highlighting greater variability in the results.

Figure 10 shows a graph of the variation coefficients as a function of the fan air velocity.

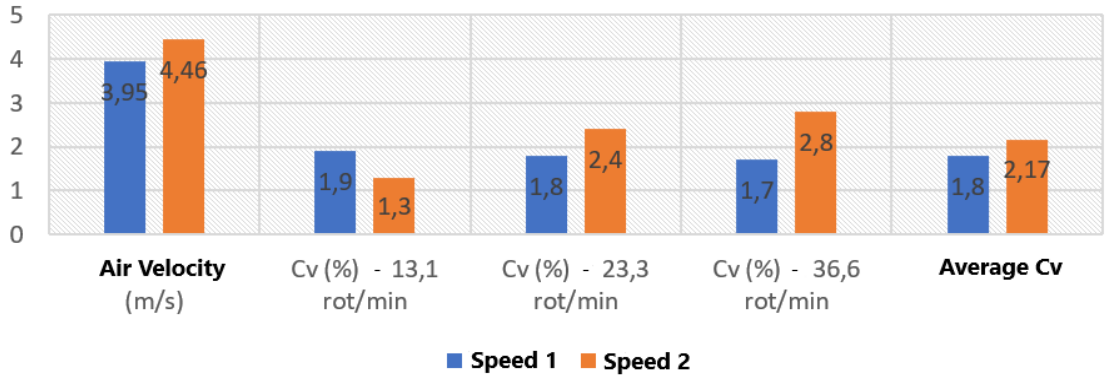

Fig. 10 - Graphical representation of the values of the coefficients of variation as a function of the fan air velocity

The coefficient of variation (Cv) increases slightly with air velocity, indicating greater sensitivity of the system to speed and turbulence. At 3.95 m/s, Cv remains relatively stable (1.7–1.9%), while at 4.46 m/s more variable values are observed, between 1.3% and 2.8%. The results suggest that higher air velocity can increase the average mass collected, but also the variability of measurements, especially at high combinations of rotational speed and velocity.

Table 3 shows the results obtained from measuring the soil penetration resistance in the experimental plot, and Table 4 shows the soil moisture values determined under the same test conditions.

Table 3

No.	Depth, cm	Average soil resistance to penetration (psi) in the vineyard	Average soil resistance to penetration (psi) in the fruit tree plantation
1	0-10	200	170
2	10-20	220	180
3	20-30	240	200

Table 4

Rehearsal	Soil moisture (%) in the vineyard	Soil moisture (%) in the fruit tree plantation
1	20.9	25,0
2	21,2	25,2
3	21,8	25,4
Media	21,3	25,2

Soil penetration resistance shows that the topsoil (0–10 cm) offers good growing conditions, while the 10–30 cm layers fall within the moderate compaction zone. The average values recorded (200 psi for fruit trees and 240 psi for vines) suggest that root development and water infiltration may be slightly limited.

Compaction may be influenced by low moisture at the time of testing, but even without intensive agricultural activity, there is the possibility of a dense layer in the surface soil profile. Regular monitoring and, if necessary, light aeration work is recommended to maintain healthy soil.

Based on this data, the actual sowing rate was calculated according to the relationship shown, to ensure accurate and optimal seed application.

$$N_{rel} = \frac{m}{S} \times 10000, kg/ha \quad (4)$$

$$Deviation = \frac{N_{real} - N_{theoretically}}{N_{theoretically}} \times 100, \% \quad (5)$$

Table 5 shows the field tests carried out with the innovative equipment for sowing grass between rows of vines, and Table 6 shows the tests carried out between rows of fruit trees.

Table 5

Measurements (cm)	Deviation (%)	Description	Value
7,8	2,50	Target value	8,00
8,2	2,50	Average of measurements	8,17
8,5	6,25	Average deviation (%)	3,75
		Standard deviation	0,35
		Coefficient of variation	4,29

Table 6

Measurements (cm)	Deviation (%)	Description	Value
8,2	2,50	Target value	8,00
8,0	0,00	Average of measurements	8,27
8,6	7,50	Average deviation (%)	3,33
		Standard deviation	0,31
		Coefficient of variation	3,75

CONCLUSION

Tests carried out with innovative equipment for sowing grass between rows of vines and fruit trees showed good accuracy in terms of both sowing rate and working depth of the machine. The recommended technological rate for the grass mixture is 60 kg/ha, and a value of 64 kg/ha was recorded in the field, exceeding the plan by 6.67%. This deviation, which is less than 10%, is considered normal in practical conditions and may be acceptable if a higher crop density is desired; however, it can lead to additional seed consumption and, in some cases, denser plant growth, which can affect crop uniformity.

The working depth of the machine was adjusted with precision, keeping the seeds in the optimal layer of 1–2 cm, which is essential for uniform germination and rapid development. In tests between rows of vines, the average deviation was 3.75%, the coefficient of variation was 4.29%, and the standard deviation was 0.35 cm, indicating high consistency and stability. For tests between rows of fruit trees, the average deviation was 3.33%, the coefficient of variation was 3.75%, and the standard deviation was 0.31 cm, confirming the precise and consistent adjustment of the machine.

The results show that the equipment ensures uniform seed distribution and stable working depth, complying with recommended technological standards, reducing seed loss and promoting uniform

germination and grass development. However, periodic recalibration of the device is recommended to maintain optimal long-term performance.

ACKNOWLEDGEMENT

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THE EVOLUTION OF THE RESEARCH, DEVELOPMENT AND INNOVATION SYSTEM IN ROMANIA AND ITS POTENTIAL IMPACT ON RURAL DEVELOPMENT

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EVOLUȚIA SISTEMULUI DE CERCETARE-DEZVOLTARE-INOVARE ÎN ROMÂNIA ȘI IMPACTUL SĂU POTENȚIAL ASUPRA DEZVOLTĂRII MEDIULUI RURAL

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Keywords: *research, development, innovation, digitalization, artificial intelligence, rural environment, applied research, territorial disparities, România*

ABSTRACT

In the context of Romania's efforts to align with the European Union's green, digital, and cohesive development priorities, this study analyzes the evolution of the national research, development, and innovation (RDI) system between 2019 and 2023. Using official statistical data (INS) and recent scientific literature, the paper explores key indicators such as the number and age distribution of researchers, regional RDI investments, and the thematic focus of publicly funded projects. The results highlight both quantitative growth and territorial imbalances, with a strong concentration of resources in urban centers and underrepresentation of rural areas in applied research domains such as agriculture, energy, and digital infrastructure. The S.W.O.T. analysis reveals the strengths (well-qualified human resources, increased project funding in agriculture), weaknesses (limited youth involvement, institutional volatility), and external factors influencing the system's capacity to contribute to rural development. The paper advocates for a territorial rebalancing of RDI efforts through local partnerships, regional innovation centers, and public policies supporting sustainable development in rural communities.

REZUMAT

În contextul eforturilor României de a se alinia priorităților europene privind tranziția verde, digitalizarea și coeziunea teritorială, studiul analizează evoluția sistemului național de cercetare-dezvoltare-inovare (CDI) în perioada 2019–2023. Pe baza datelor statistice oficiale (INS) și a literaturii științifice recente, lucrarea evaluează indicatori-cheie precum numărul și structura de vârstă a cercetătorilor, distribuția regională a investițiilor CDI și tematica proiectelor finanțate public. Rezultatele evidențiază o creștere cantitativă, dar și dezechilibre teritoriale semnificative, cu o concentrare a resurselor în centrele urbane și o reprezentare redusă a mediului rural în domenii aplicate precum agricultura, energia sau infrastructura digitală. Analiza S.W.O.T. surprinde punctele forte (resurse umane bine calificate, creșterea proiectelor în agricultură), punctele slabe (implicarea scăzută a tinerilor, instabilitate instituțională) și factorii externi care influențează capacitatea sistemului CDI de a contribui la dezvoltarea rurală. Lucrarea pledează pentru o reechilibrare teritorială a eforturilor de cercetare, prin parteneriate locale, centre regionale de inovare și politici publice orientate spre dezvoltare durabilă în comunitățile rurale.

INTRODUCTION

In the context of the European Union's new priorities regarding the green transition, digitalization, and territorial cohesion, national research-development-innovation (RDI) systems are becoming essential links in shaping the economic and social future of member states. Romania, as a country in the process of consolidating its scientific and technological capacity, is currently at a critical juncture where the development directions of the RDI system can significantly influence both urban dynamics and the transformation of rural areas. The rural zone covers 89.6% of Romania's territory and houses 46.4% of the population, well above the EU average of 29.1% (*Popescu et al., 2022*).

In this context, the present article aims to analyze the recent developments of the RDI system in Romania during the period 2019–2023, based on official statistical data provided by the National Institute of Statistics (INS). By evaluating key indicators (such as the number of researchers, scientific field structure,

public investments by region, and the typology of RDI programs), the paper seeks to identify major trends, territorial imbalances, and dominant themes in publicly funded research.

The general objective of the study is to assess to what extent the RDI system contributes (directly or indirectly) to rural development, through the lens of funded resources, infrastructures, and research themes. Romania's rural population is undergoing an accelerated process of aging and depopulation, amid migration and natural decline (*Popescu et al., 2022*). Additionally, the analysis is complemented by a S.W.O.T. examination, which synthesizes the strengths and weaknesses of the current system, as well as the opportunities and threats that may shape its strategic future.

In the context of intensified climate change, sectors such as tourism have begun to experience direct pressures, but also to identify opportunities for regional development, particularly through infrastructure adaptation and diversification of offerings. According to a recent study, more favorable climatic conditions have increased the attractiveness of certain tourist regions in Romania (*Marcuta et al., 2025*). Rising land temperatures and erratic precipitation are already affecting Romanian rural zones such as Dobrogea, where agriculture is under pressure due to prolonged droughts. This highlights the urgency of integrating climate adaptation with innovation strategies in rural areas (*Buzatu et al., 2024*).

Romanian rural areas are exposed to a combination of climate, financial, and technological risks, and strengthening their capacity to manage these is essential for a sustainable development model (*Ghiuleanu et al., 2023*).

The paper is intended for researchers, decision-makers, regional development practitioners, and stakeholders interested in creating data-driven public policies aimed at capitalizing on the innovative potential of less-developed regions in Romania.

MATERIALS AND METHODS

The study was developed based on a descriptive and interpretative analysis methodology, combining official statistical data provided by the National Institute of Statistics (INS) for the period 2019–2023 with a selection of relevant scientific sources from recent literature on research-development-innovation (RDI) and its impact on rural development. The following statistical TEMPO codes from INS were used: TEMPO_CDP102D, TEMPO_CDP102H, TEMPO_CDP102B, TEMPO_CDP102G, TEMPO_CDP104B, TEMPO_CDP105A, TEMPO_CDP101B, covering indicators such as:

- the number of researchers by field and age group;
- distribution of RDI personnel by gender, education level, and occupation;
- public expenditure on RDI by development regions;
- number of funded RDI projects, according to the NABS 2007 classification;
- number of active research and development units by institutional sectors.

For an in-depth understanding of the context, statistical data were correlated with specialized literature addressing topics such as: the impact of climate change on agriculture and society (*Buzatu et al., 2024*), soil conservation (*Buzatu et al., 2023*), risks in crop management (*Ghiuleanu et al., 2023*), integration of artificial intelligence in farms (*Plesa et al., 2024*), corporate social responsibility (*Marcuta and Marcuta, 2023*), digitalization in rural education (*Rosu et al., 2022*), and perceptions of rural inequalities (*Popescu et al., 2022*).

The tools used in the analysis process included:

- quantitative analysis (charts and comparative tables by year and region, Excel Sheets 365);
- spatial analysis (geographical distribution of resources and investments);
- typological analysis (classification of projects by theme and funding source);
- S.W.O.T. analysis to synthesize the strengths and weaknesses of the RDI system in Romania in relation to the specific challenges and opportunities of rural development.

The data were interpreted in correlation with European priorities on the green and digital transition (*European Commission, 2024*), with the social and demographic evolution of the rural population, as well as with trends in digitalization and social responsibility among economic actors (*Marcuta et al., 2025*).

Finally, the methodology was completed by an interdisciplinary approach, which allowed for the integration of economic, social, and technological dimensions of innovation in the rural environment. The results obtained provide a solid basis for formulating public policies aimed at reducing territorial disparities and supporting a rural development model based on applied research and inclusive innovation.

RESULTS

The results section aims to highlight the dynamics of the research-development-innovation (RDI) system in Romania during the 2019–2023 period, based on key indicators: the distribution of researchers by scientific field and age group, the structure of RDI employees by gender and education level, the volume of RDI expenditures by development regions, as well as the evolution of funded RDI projects according to the NABS 2007 classification. The presentation of these data seeks to identify significant trends at both regional and national levels that can support hypotheses regarding the potential impact on rural development.

This descriptive analysis will integrate both quantitative interpretations (through tables and graphs) and spatial ones (regional thematic maps), contributing to a better understanding of how human, financial, and institutional resources involved in RDI are distributed, as well as the potential relationship between RDI intensity and rural development in Romania.

a) Researchers in RDI activity by scientific fields

The chart highlights the evolution of personnel involved in research and development in Romania, broken down by main scientific fields, during the period 2019–2023. Although the total number of researchers has shown a steady increase (+14.8% in 2023 compared to 2019), the dynamics across fields reveal significant imbalances.

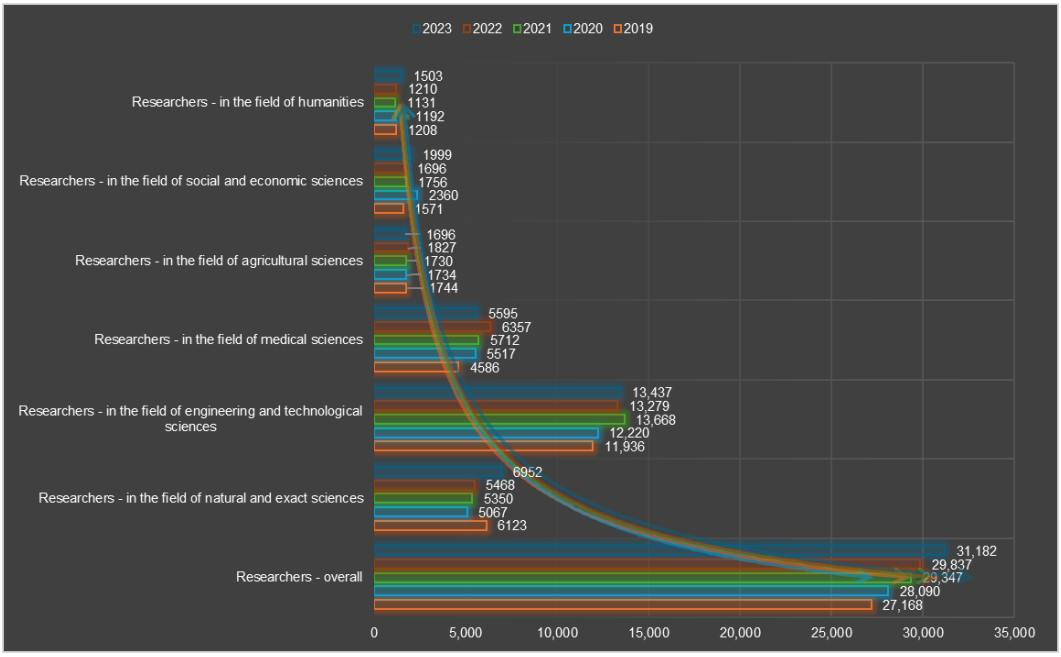


Fig. 1 - Distribution of research and development personnel by scientific fields in Romania, U.M. = number
(NIS, http://statistici.insse.ro)

I. The field of engineering and technological sciences remains dominant, maintaining relatively stable numbers, with a peak in 2021 (13,668 researchers), followed by a slight decline. This stability indicates a concentration of resources in areas with immediate economic applicability, which is relevant for technology transfer (including to rural environments), in precision agriculture, infrastructure, or renewable energy.

II. Natural and exact sciences experienced a sharp drop in 2020, but a strong rebound in 2023, even surpassing the 2019 level (+13.5%). This recovery can be associated with increased investments in fundamental research in the post-pandemic period (*Eurostat, 2022*), as well as allocations through the NRRP for frontier domains (*Ministerul Educației și Cercetării, 2025*).

III. Medical sciences saw a clear increase between 2019 and 2022 (+38.6%), likely accelerated by the COVID-19 pandemic, but followed by a decline in 2023 (possibly a signal of redirected funding).

IV. Agricultural sciences have stagnated or even slightly regressed, consistently remaining below 6% of the total number of researchers. Considering the importance of agriculture for rural areas, this low share represents a strategic risk for the sustainability of innovation-based rural development. Although Romania's agricultural areas have undergone only minor changes in recent years, maintaining productivity is closely linked to implementing effective soil degradation prevention strategies (*Buzatu et al., 2023*). The integration of artificial intelligence into farm operations is increasingly contributing to the efficiency and sustainability of rural areas, representing a priority direction in current applied research (*Plesa et al., 2024*).

V. Social and economic sciences, as well as the humanities, have experienced more pronounced variations without a clear trend. These fluctuations may reflect either intermittent funding or the lack of coherent policies to integrate these fields into the RDI ecosystem.

This imbalanced distribution across fields raises important questions regarding national research prioritization in relation to Romania's socio-economic needs, especially in the context of reducing urban–rural disparities (*INS, 2024*).

b) Researchers in RDI activity by age groups

The data reveal an important reality regarding the generational structure of researchers in Romania between 2019 and 2023. Although the total number of researchers increased steadily from 27,168 in 2019 to 31,182 in 2023 (+14.8%), the distribution by age group raises concerns about the RDI system's capacity to attract and retain young talent.

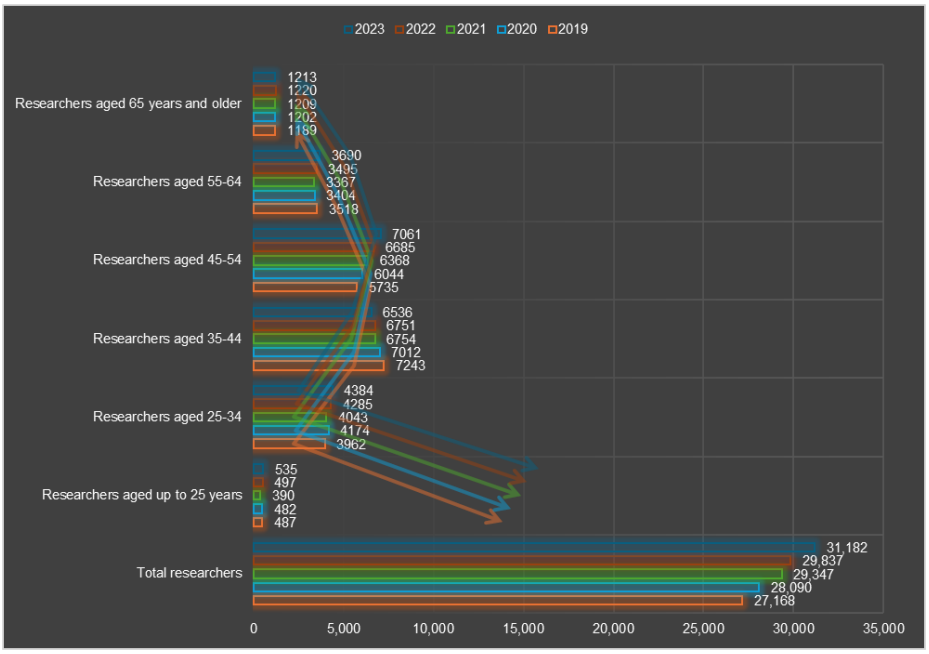


Fig. 2 - Evolution of human resources in research and development by age group, U.M. = number
(NIS, http://statistici.insse.ro)

I. Young people under the age of 25 consistently represented less than 2% of all researchers. Although there was a slight increase in 2022 and 2023 (from 390 in 2021 to 535 in 2023), this does not compensate for earlier declines and suggests low attractiveness of a scientific career among the very young. This trend may reflect obstacles such as low entry-level salaries, career uncertainty, and lack of structured mentorship (*Akhalkatsi and Kapil, 2022*).

II. The 25–34 age group, relevant for young researchers in the early stages of their post-university or doctoral careers, increased slightly over the five-year period (+422 individuals). However, proportionally, the growth rate is slow relative to the need for human resource renewal.

III. In contrast, the majority of researchers fall into the 35–44 and 45–54 age categories, with a tendency to shift towards the older groups. The number of researchers aged 45–54 increased by 23% over the analyzed period, while the 35–44 category decreased by nearly 10%.

IV. The aging of the system is also evident in the 55–64 age group, which has slightly increased in recent years, and in the 65+ category, where the figures have remained steady but significant (over 1200 researchers annually).

This evolution highlights pressure on generational renewal in research, with potential negative effects on the flexibility and adaptability of the RDI ecosystem. In rural areas, where innovation requires the involvement of researchers in agriculture, territorial development, environment, or infrastructure, attracting young people is all the more important to connect research with the needs of local communities.

c) Employees in research and development by occupation and gender

The data reflect a complex picture of the occupational and gender structure of research and development personnel in Romania. Between 2019 and 2023, the total number of RDI employees increased

moderately, from 43,973 to 48,103 (+9.4%), and the gender distribution remained relatively stable, with a slight increase in the absolute number of women.

Table 1

Occupational and gender distribution of personnel involved in research and development activities

Grouping by occupation of the number of employees in research and development	Genders	2019	2020	2021	2022	2023
		U.M.: Number of persons				
Overall	Overall	43,973	45,304	47,011	49,052	48,103
	Male	23,721	24,088	25,394	26,929	25,921
	Female	20,252	21,216	21,617	22,123	22,182
Researchers	Overall	27,168	28,090	29,347	29,837	31,182
	Male	14,423	14,815	15,666	16,078	16,680
	Female	12,745	13,275	13,681	13,759	14,502
Technicians and similar occupations	Overall	6195	6674	7531	8845	6535
	Male	3517	3685	4585	5587	3914
	Female	2678	2989	2946	3258	2621
Other categories of employees	Overall	10,610	10,540	10,133	10,370	10,386
	Male	5781	5588	5143	5264	5327
	Female	4829	4952	4990	5106	5059

(NIS, http://statistici.insse.ro)

I. The category of researchers (the core of RDI activity) has grown steadily, reaching 31,182 in 2023 (+14.8% compared to 2019). The gender structure remains relatively balanced: women represent approximately 46% of all researchers, which is a good performance in the regional and European context.

II. Among technicians and associated personnel, a significant increase was observed until 2022, followed by a notable drop in 2023 (from 8845 to 6535, or -26.1%). This fluctuation may be linked to changes in employment policies or the completion of time-bound projects with specific funding. It is important to note that men are the majority in this category, although women maintain a steady presence of around 40%.

III. As for other employee categories (administrative staff, support, etc.), the number remained stable over the past five years, around 10,000 people, with a balanced gender distribution.

This stable structure suggests an RDI ecosystem with a relatively well-defined human resource component, though exposed to risks in the technical area, where fluctuations are high. Moreover, the relatively equitable involvement of women in research contrasts positively with other STEM fields in Romania and the region (*European Institute for Gender Equality, 2023*). In rural areas, where the presence of technicians and the formation of mixed teams are essential for the application of research results, these imbalances may affect the local implementation capacity of innovation.

d) Employees in research and development by educational level and gender

The analysis of the qualification structure of employees in research and development highlights a predominantly academic and university-level professional profile, typical of a system focused on specialized expertise. Between 2019 and 2023, the share of personnel with higher education remained high, consistently representing over 85% of the total CDI workforce. Although 2023 shows a slight decrease compared to the previous year (from 42,573 to 40,873 people), this level remains robust and indicates a strong degree of professional continuity in the sector.

Table 2

Qualification level of research and development personnel

Level of training of research and development employees	Genders	2019	2020	2021	2022	2023
		U.M.: Number of persons				
Overall	Overall	43,973	45,304	47,011	49,052	48,103
	Male	23,721	24,088	25,394	26,929	25,921
	Female	20,252	21,216	21,617	22,123	22,182
Superior preparation	Overall	37,392	39,349	40,320	42,573	40,873
	Male	19,927	20,571	21,336	23,007	21,381
	Female	17,465	18,778	18,984	19,566	19,492
Of which doctoral studies	Overall	18,249	18,756	18,982	20,086	19,492

	Male	9263	9491	9557	10,439	9715
	Female	8986	9265	9425	9647	9777
Other education (exclusively higher)	**Overall**	6581	5955	6691	6479	7230
	Male	3794	3517	4058	3922	4540
	Female	2787	2438	2633	2557	2690

(*NIS, http://statistici.insse.ro*)

I. One important observation is the stability and significant proportion of personnel with doctoral studies (over 18,000 individuals annually, representing approximately 45–47% of the total RDI workforce). This share supports the system's capacity to conduct advanced research projects and to generate innovative outcomes, particularly in competitive or strategic fields.

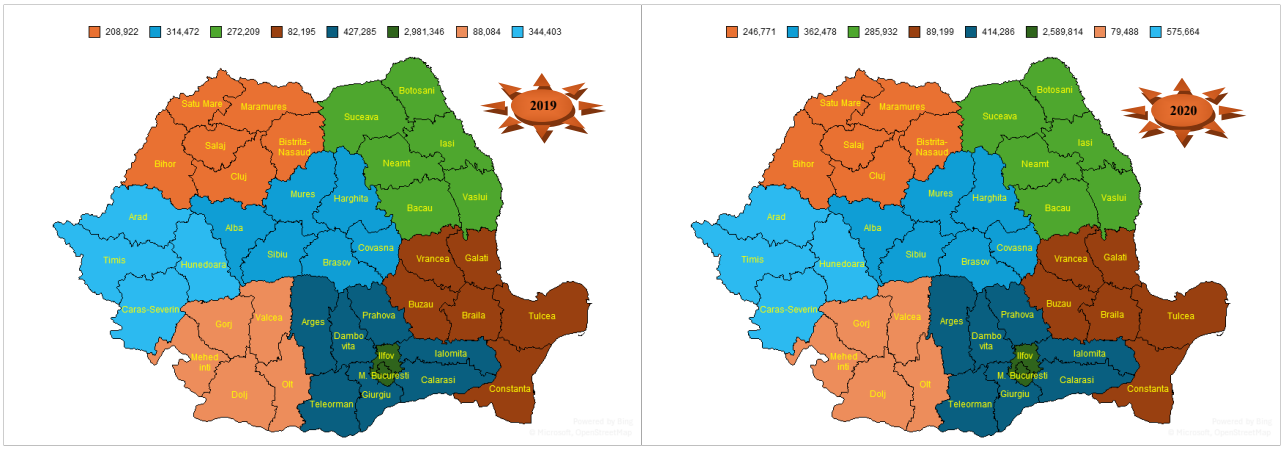
II. The gender distribution is balanced both at the level of higher education and among those holding a PhD, where women have an almost equal presence to men during 2022–2023. In fact, in 2023, the number of women with a PhD slightly exceeded that of men (9777 compared to 9715), which is a positive signal regarding gender equity in advanced academic careers.

III. The category of personnel with other (non-higher) education levels is significantly smaller and has fluctuated over the years, with an increase in 2023. This category is male-dominated but plays a marginal role in the overall RDI workforce structure.

This highly qualified structure is a strong point of the RDI system; however, it must be aligned with the challenges of integrating research into the economy and society, particularly in rural areas. There, knowledge transfer requires not only theoretical expertise, but also practical and technological capacities in fields such as agriculture, environment, and community development (*European Commission, 2024*).

e) Total research and development expenditures by development region

Expenditures for research and development (R&D) activities in Romania reveal significant regional disparities, with a strong concentration in the Bucharest–Ilfov region and modest investments in predominantly rural areas. Divided into current expenditures (operations, salaries, materials) and capital expenditures (investments, equipment, infrastructure), the data for the 2019–2023 period highlight several clear trends:



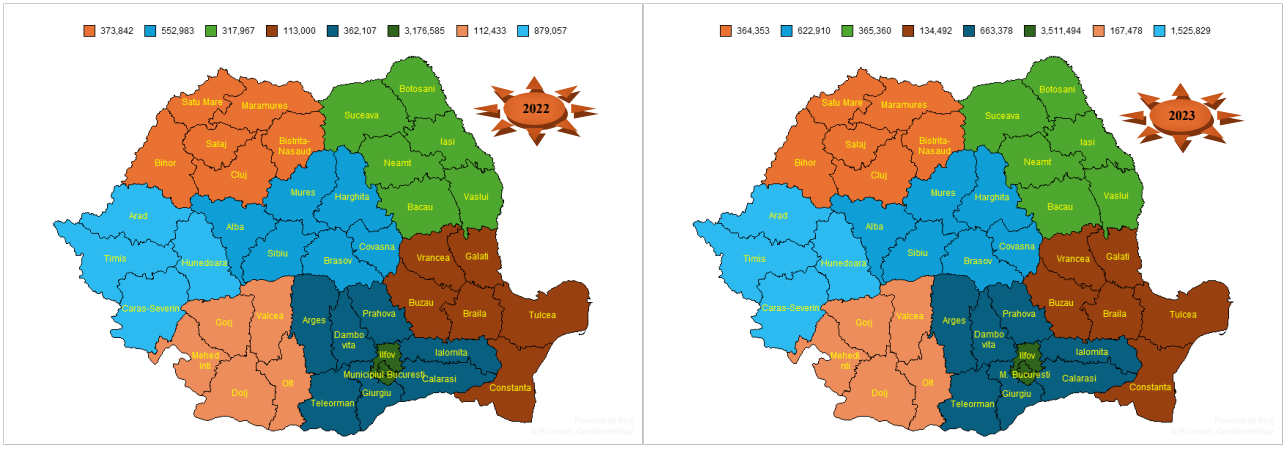


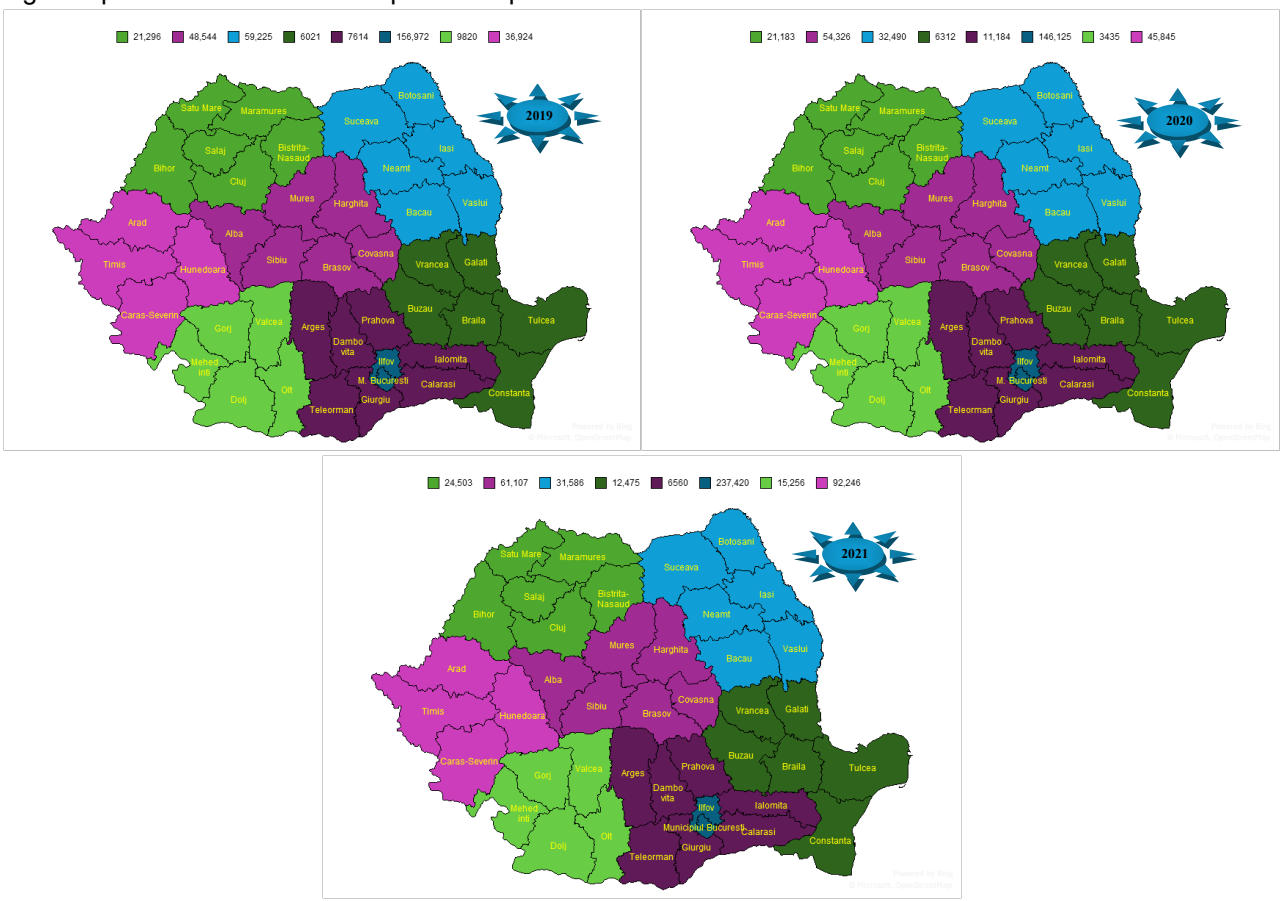
Fig. 3 - Geographical distribution of public expenditures for research and development in Romania (current), unit: thousand RON

(NIS, http://statistici.insse.ro)

I. The Bucharest–Ilfov region clearly dominates allocations, reaching over 3.5 billion RON in 2023, by far the largest investment in the country. This concentration is linked to the presence of top universities, national research institutes, and private R&D centers, but it also reinforces the territorial polarization of research (*Eurostat, 2024*).

II. Regions with high rural potential, such as North-East and South-East, receive relatively small amounts (365 million RON and 134 million RON in 2023), despite major needs for agricultural innovation, territorial development, and infrastructure.

III. The West region recorded a remarkable increase, from 344 million RON in 2019 to 1.52 billion RON in 2023, a sign that RDI investments can be effectively redirected outside the capital if supported by regional policies and institutional partnerships.



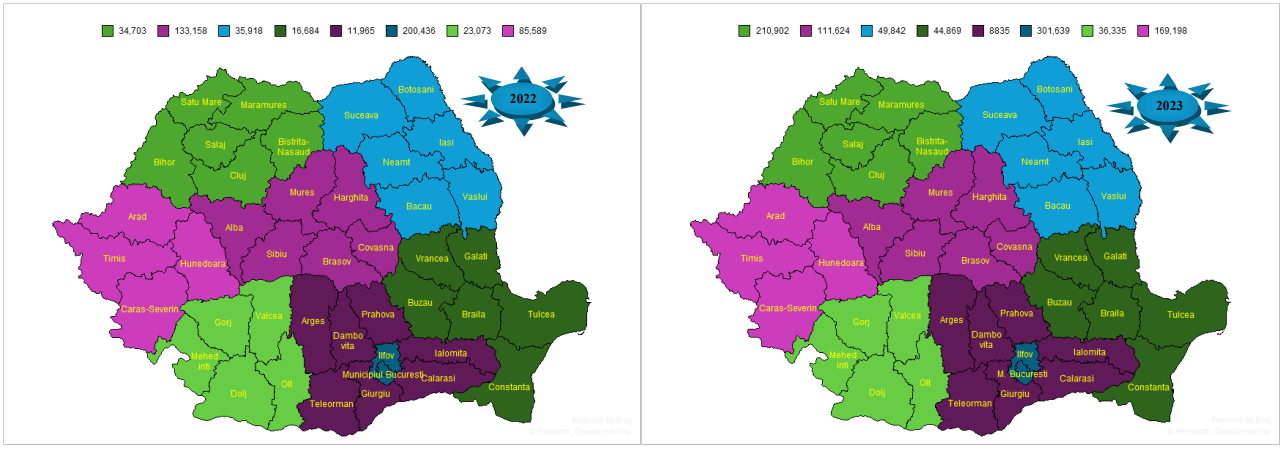


Fig. 4 - Geographical distribution of public capital expenditures for research and development in Romania, unit: thousand RON

(NIS, http://statistici.insse.ro)

I. The situation is even more unbalanced when it comes to infrastructure and equipment investments. Bucharest–Ilfov consistently concentrates the largest share of capital expenditures (301 million RON in 2023).

II. The North-West region recorded a spectacular jump in 2023 (from 34 million to 210 million RON), suggesting a possible strategic reorientation of investments in this area (an interesting case for impact analysis).

III. Other regions such as South-Muntenia, South-West Oltenia, or South-East continue to register low levels of capital investment, reflecting structural underfunding of research in rural areas.

The territorial disparities highlighted by these data confirm that rural areas are indirectly affected by the geographic polarization of research, through the lack of investments in institutes and equipment that could support the specific needs of local communities (sustainable agriculture, green energy, rural digitalization). The integration of research into regional development remains an insufficiently achieved objective.

The digitalization of the educational process plays an increasingly important role in developing the professional skills necessary for labor market integration and is perceived by young people as an essential factor for adapting to the new requirements of the modern economy, including in rural regions (*Rosu et al., 2022*).

f) Research and Development Projects, According to NABS Classification

Data on RDI programs structured according to the NABS 2007 classification reveal significant trends in the thematic priorities of research in Romania. The total number of projects varied from 7620 in 2019 to 7099 in 2023, with a peak reached in 2022 (9151 projects). Although this evolution is generally positive, a detailed domain-specific analysis reveals important discrepancies between declared priorities and those actually financed.

Table 3

Evolution of research and development programs by thematic areas according to the NABS 2007 classification

Types of research and development programs according to NABS 2007	2019	2020	2021	2022	2023
	U.M. = Number				
Total, of which, on NABS programs:	7620	7700	8507	9151	7099
Exploration and exploitation of land	121	65	97	128	70
Environment	286	431	393	489	291
Space exploration and exploitation	63	45	26	28	24
Transport, telecommunications, and other infrastructure	90	121	116	145	221
Energy	140	101	75	85	107
Industrial production and technology	477	489	567	700	414
Health	494	426	479	455	321
Agriculture	675	818	888	1322	1041
Education	290	264	233	320	260
Culture, recreation, religion, and media	170	129	192	138	218
Political and social systems, structures, and processes	144	88	47	117	135

General promotion of knowledge: research and development funded by general university funds (GUF) for:	1858	2282	2589	2499	1500
Natural and exact sciences	1319	1444	1437	1409	541
Engineering and technological sciences	297	454	617	487	402
Medical and health sciences	44	58	32	40	42
Agricultural sciences	52	51	68	83	80
Social and economic sciences	130	212	280	314	332
Humanities	16	63	155	166	103
General promotion of knowledge: research and development funded from sources other than general university funds, for:	2597	2237	2576	2584	2367
Natural and exact sciences	796	683	835	938	648
Engineering and technological sciences	1028	958	888	887	994
Medical and health sciences	39	48	239	52	41
Agricultural sciences	22	31	26	33	110
Social and economic sciences	299	197	220	302	216
Humanities	413	320	368	372	358

(*NIS, http://statistici.insse.ro*)

1) Relevant areas for the rural environment:

I. *Agriculture* stands out positively, with a substantial increase in the number of projects, peaking in 2022 (1322 projects), followed by a slight decline in 2023. This trend suggests a growing recognition of agriculture's role in rural innovation, with significant potential impact.

II. *The environment* and *transport/infrastructure* show a favorable evolution. The number of infrastructure-related projects more than doubled between 2019 and 2023 (from 90 to 221), reflecting investments in digitalization and mobility (essential for integrating rural areas).

III. *Energy* and *land use* fluctuated, maintaining relatively low levels (an ongoing challenge given the broader goals of green transition and sustainability in isolated communities).

2) Support and general knowledge promotion domains:

I. General knowledge promotion programs (GUF), especially those dedicated to exact and engineering sciences, recorded a marked decline in 2023. The number of projects in natural sciences funded from university budgets dropped by over 60% compared to 2019. This may reflect either a shift in funding priorities or a deficit of sustained academic initiatives.

II. Programs funded from non-university sources (likely including European or private funding) remained relatively stable, particularly in engineering and social sciences, suggesting an increasing reliance on competitive financing. The involvement of companies in social responsibility activities (including non-financial reporting and community-focused projects) illustrates a growing alignment between economic performance and sustainable development (*Marcuta and Marcuta, 2023*).

3) Domains with significant decline:

I. *Health*, a central area during the pandemic, peaked in 2021 (479 projects), but experienced a sharp decline by 2023 (321 projects).

II. *Space exploration and exploitation* remains marginal, with a clearly declining trend.

III. *Culture, religion, and mass media* have shown a fluctuating evolution, likely reflecting punctual or contextual projects.

The structure of R&D programs in Romania reveals a mixed thematic orientation, in which certain key domains for rural development (such as agriculture, infrastructure, and the environment) are gaining ground, while other essential areas (such as energy or health) face instability. A coherent funding policy should aim for continuity of investments in applied fields that have a direct impact on local communities, particularly in light of European green and digital transition strategies.

g) Units with research and development activity, by performance sectors

The evolution of the number of entities engaged in research and development (R&D) activities in Romania between 2019 and 2023 reflects significant institutional fluctuation, particularly in the private sector.

This may indicate challenges related to the stability and sustainability of actors involved in the national RDI system.

Table 4

Distribution of research and development units by performance sectors

Performance sectors	2019	2020	2021	2022	2023
	U.M.: Number				
Total of which:	480	621	550	556	468
Public sector	259	252	249	252	247
- government sector	174	168	165	169	166
- higher education sector	85	84	84	83	81
Private sector	221	369	301	304	221
- business sector	204	346	281	285	198
- private non-profit sector	17	23	20	19	23

(NIS, http://statistici.insse.ro)

I. The total number of RDI units increased sharply in 2020 (from 480 to 621), only to gradually decline, reaching 468 in 2023 (below the 2019 level). This trend suggests a temporary surge, possibly driven by the launch of one-off funded projects (e.g., POC/PNRR funds), followed by the consolidation or withdrawal of actors lacking long-term institutional capacity.

II. The public sector remained relatively stable, with a slight decrease in the number of units (from 259 to 247). Within this sector, governmental institutions (national institutes, institutes of the Academy) are predominant, while higher education holds a modest presence, with only 81 units in 2023, slightly down. This situation raises questions about the role of universities in RDI and their capacity to generate and implement applied research, including in support of rural development.

III. The private sector was the most volatile. After a dramatic increase in 2020 (+66.9% compared to 2019), the number of units fell back to the initial level by 2023 (221). Among them, the business sector holds an overwhelming share, while non-profit organizations are few and institutionally unstable (only 23 in 2023). This indicates a lack of continuity in RDI partnerships with civil society—an important obstacle to participatory innovation in rural areas.

These data confirm that Romania's research institutional infrastructure still relies heavily on public initiatives, while the private and non-profit sectors remain fragile, volatile, and underrepresented. For innovation to reach the local level (including rural communities), there is a need for local RDI centers, mobile research units, regional public-private partnerships, and a university system anchored in territorial needs.

S.W.O.T. analysis

Following the analysis of the evolution of the research-development-innovation (RDI) system in Romania during the period 2019–2023, it becomes necessary to undertake an integrative approach that synthesizes the strengths and vulnerabilities of the system, while also highlighting the opportunities and threats that influence its capacity to contribute to rural development. The S.W.O.T. method provides an effective strategic framework for this evaluation, allowing for a critical understanding of the resources, limitations, and the broader context in which the RDI system operates.

This analysis does not aim merely to inventory relevant internal and external factors, but rather to shed light on the interaction between research and territory: how well prepared is the RDI system to meet the needs of rural communities, what gaps may hinder the transfer of innovation, and which levers could be activated to reduce territorial disparities.

In this regard, the S.W.O.T. analysis becomes a strategic guidance tool, useful not only for understanding the current context but also for formulating coherent public policies adapted to local realities.

Table 5

S.W.O.T. Analysis: The RDI System in Romania and Its Potential Impact on the Rural Environment (2019–2023)

Strengths	Weaknesses
I. Increase in the total number of researchers (+14.8%).	I. Low proportion of researchers under 35 years old (risk of system ageing).
II. Dominance of engineering and technological fields (with direct economic applicability).	II. Underfunding of research in agriculture and energy sectors, crucial for rural development.
III. Significant share of researchers holding PhDs	III. Major regional disparities (Bucharest accounts for over

(≈45%).	50% of total funding).
IV. Numerous RDI projects in agriculture and infrastructure (2022–2023).	IV. Limited presence of RDI units in the private non-profit sector.
V. Relatively good gender balance among researchers and highly qualified staff.	V. Institutional instability in the number of RDI units (decline after 2020).
Opportunities	**Threats**
I. Development of RDI infrastructure in North-West and West regions (positive trend).	I. Risk of knowledge polarisation (regional gaps may limit rural access to innovation).
II. RDI programmes focused on agriculture and rural digitalisation (aligned with PNRR funding).	II. Intermittent funding and lack of a coherent rural innovation strategy.
III. Public–private partnerships in applied research.	III. Low attractiveness of research careers for young people (under 2% are under 25 years old).
IV. EU policies supporting knowledge-based rural development (e.g., Smart Villages).	IV. Lack of a research culture in rural areas (weak infrastructure and limited access to RDI outcomes).

(Source: Own determination.)

The S.W.O.T. analysis reveals that Romania's RDI system benefits from a highly qualified human resource base and shows a positive development trend in certain regions and fields. However, it is hindered by regional disparities, institutional stagnation, and challenges in attracting young researchers. In the context of rural development, opportunities can only be capitalized upon through coherent policies aimed at decentralizing research, supporting local partnerships, and investing in applied infrastructure beyond urban centers.

CONCLUSIONS

The analysis of the evolution of Romania's research-development-innovation (RDI) system during the 2019–2023 period reveals both significant progress and structural limitations that affect its capacity to directly support rural development. Amid a steady increase in the number of researchers and investments in certain regions (e.g., West, North-West), the RDI system is gradually strengthening its potential to generate knowledge and facilitate technology transfer.

However, marked disparities persist across domains and territories. Strategic fields for rural development (such as agriculture, sustainable energy, local infrastructure, and social innovation) remain underfunded compared to others. At the same time, the geographical polarization of resources continues to pose a major challenge: the Bucharest–Ilfov region still absorbs over half of the national RDI funds, while predominantly rural regions receive modest investments and have weak institutional presence.

The human resource structure in research indicates an aging system and a low participation rate of young people under 35, raising concerns about the long-term sustainability of the RDI ecosystem. Nevertheless, the high proportion of personnel with doctoral training and the gender balance among researchers are key strengths.

To truly leverage the RDI system's potential for the benefit of rural communities, a paradigm shift is required: moving from an urban-centric research model to an integrated territorial approach that supports applied innovation in agriculture, environment, infrastructure, and local public services. In this regard, supporting local partnerships, creating regional RDI centers, and encouraging applied research in universities outside the capital could represent concrete steps toward reducing territorial disparities and fostering the sustainable development of rural areas.

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THE CONTRIBUTION OF ENVIRONMENTAL INVESTMENTS TO THE SUSTAINABILITY OF THE RURAL ENVIRONMENT IN ROMANIA
/
CONTRIBUȚIA INVESTIȚIILOR ECOLOGICE LA SUSTENABILITATEA MEDIULUI RURAL ÎN ROMÂNIA

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Keywords: *environmental investments, sustainable rural development, Romania, environmental statistics, public administration, green transition, ecological expenditure, S.W.O.T. analysis,*

ABSTRACT

This paper analyzes the dynamics of environmental protection investments and expenditures in Romania between 2019 and 2023, highlighting their implications for the sustainable development of rural areas. The study utilizes official statistical data from the National Institute of Statistics, complemented by scientific literature and policy documents, to assess the allocation of financial resources by environmental domain, region, and type of stakeholders (specialized producers, non-specialized producers, and public administration). Results show an increasing trend in ecological spending, especially in waste management and resource conservation, but also point to imbalances between rural and urban investments. The S.W.O.T. analysis confirms both the green transition potential of rural areas and the persistent challenges related to investment efficiency and administrative capacity. This research offers an integrative perspective on the connection between environmental policy and rural development, emphasizing the need for coherent and sustained strategic interventions.

REZUMAT

Lucrarea analizează dinamica investițiilor și cheltuielilor pentru protecția mediului în România în perioada 2019–2023, evidențiind implicațiile acestora asupra dezvoltării durabile a mediului rural. Studiul valorifică date statistice oficiale de la Institutul Național de Statistică, completate de surse științifice și documente de politici publice, pentru a evalua alocarea resurselor financiare pe domenii de mediu, județe și tipuri de actori implicați (producători specializați, nespecializați și administrația publică). Rezultatele relevă o tendință de creștere a cheltuielilor ecologice, în special pentru gestionarea deșeurilor și conservarea resurselor, dar și un dezechilibru între investițiile rurale și cele urbane. Analiza S.W.O.T. confirmă atât potențialul de tranziție verde al mediului rural, cât și provocările persistente privind eficiența investițiilor și capacitatea administrativă. Lucrarea oferă o perspectivă integrativă asupra legăturii dintre politicile ecologice și dezvoltarea rurală, subliniind importanța unor intervenții strategice coerente și susținute.

INTRODUCTION

Climate crisis and environmental degradation are becoming increasingly prominent in Romania's rural areas, where the impact of economic activities on natural resources directly affects the quality of life and the sustainability of agricultural production. Multiple pressures (from intensified pollution and declining soil quality to inefficient waste management and a lack of green spaces) highlight the urgent need for ecological investments and sustainable public policies.

The growing climate risks, such as prolonged drought, soil erosion, or uncontrolled deforestation, are profoundly affecting the balance of rural ecosystems in Romania. In this context, rising temperatures and the intensification of extreme climate events pose major challenges for agriculture and ecosystems, requiring the adoption of integrated adaptation and mitigation strategies, including at the rural level (*Buzatu et al., 2024*).

Over the past five years (2019–2023), according to data from the National Institute of Statistics (INS), there has been a significant increase in environmental protection expenditures, particularly in rural areas, where the cumulative impact of intensive agriculture, pollution, and limited access to green infrastructure is acutely felt.

Adapting to these challenges cannot occur outside a framework of sustainable and responsible economic development. Thus, in the context of alignment with European standards, more and more companies are integrating environmental protection and sustainability measures into their non-financial reporting, as part of a broader corporate social responsibility strategy (*Marcuta and Marcuta, 2023*).

At the same time, rural communities must strengthen their role in the ecological transition through education, civic engagement, and the application of innovative solutions. In Romania, biodiversity (although vast and valuable) is increasingly threatened by human activity and climate change. Environmental education and awareness are essential to preserving this natural heritage (*Buzatu et al., 2023*).

Official data show an increase in public spending on water resource conservation and air pollution reduction, but also a decrease in investments in key sectors, signaling an imbalance between strategic objectives and actual budget allocations.

Recent climate changes have significantly influenced the dynamics of natural resources and climate-dependent economic sectors such as agriculture and tourism (*Marcuta et al., 2025*). In agriculture especially, these phenomena require careful risk management.

The growing climatic instability strongly impacts agricultural activity, necessitating an integrated risk management approach to protect natural resources and sustain farm viability (*Ghiuleanu et al., 2023*). In this regard, sustainable soil management becomes a critical condition.

Soil conservation represents a cornerstone in ensuring the sustainability of the rural environment, being closely linked to maintaining soil fertility, combating erosion, and protecting biodiversity (*Buzatu et al., 2023*).

This need is amplified by the requirements imposed through the European Green Deal, which provides a clear framework for sustainable development in agriculture. In the current context of the green transition and the European Green Deal, the sustainability of agricultural activities is no longer merely a choice, but a shared responsibility assumed by all actors involved in rural development (*Buzatu et al., 2024*).

Therefore, this paper analyzes the contribution of ecological investments in Romania to environmental protection and the strengthening of rural environmental sustainability, based exclusively on official statistical data provided by INS for the period 2019–2023.

MATERIALS AND METHODS

For the purposes of this research, official statistical data provided by the National Institute of Statistics (INS) were used, covering the period 2019–2023. The selected datasets targeted relevant indicators for the analysis of environmental investments and expenditures, resource consumption, land regeneration, and green space expansion, extracted using specific TEMPO codes:

- **TEMPO_PMI105A** – Environmental protection expenditures by CAEN Rev.2 activities and types of expenditures;
- **TEMPO_PMI105B** – Environmental protection expenditures by CAEN Rev.2 activities and environmental domains;
- **TEMPO_PMI116A** – Environmental tax accounts by tax categories and CAEN Rev.2 activities;
- **TEMPO_PMI113A** – Economy–environment material flow accounts;
- **TEMPO_THT0734** – DMC by types of materials;
- **TEMPO_TOE1271** – Green space area by counties;
- **TEMPO_TMJ1164** – Area of land subject to regeneration by regeneration type.

The raw data were collected, centralized, and processed using Microsoft Excel 365, which enabled efficient organization into comparative tables, trend graphs, and thematic maps of Romania, in order to highlight the territorial distribution of ecological investments and resources at the county level.

In addition to statistical data, the research integrated content analysis of several scientific articles published in peer-reviewed journals specializing in sustainable agriculture, environmental policies, and rural development. These articles were used to complement and support the quantitative interpretations, offering a conceptual and comparative framework related to climate challenges, ecological policies, and national and European adaptation strategies.

Official documents, government reports, and international platforms (such as the EEA, OECD, European Commission, Ministry of Environment, and Department for Sustainable Development) were also consulted, contributing to the contextualization of the analyzed phenomena from an integrative and cross-sectoral perspective. The entire approach was descriptive-analytical in nature, based on quantitative and comparative methods aimed at identifying relevant trends regarding rural environmental sustainability in Romania.

RESULTS

The ***"Results"*** section aims to present and interpret the available statistical data regarding ecological investments and environmental policies in Romania, with a focus on their impact in rural areas and their contribution to sustainable development.

The analysis is based exclusively on official data provided by the National Institute of Statistics (INS) for the period 2019–2023 and will examine trends, evolutions, and possible correlations between:

1. Environmental protection expenditures (by category and producer);
2. Targeted environmental domains (air, water, soil, biodiversity, etc.);
3. Economy–environment material flows (domestic consumption, extraction, imports);
4. Green space areas (by county);
5. Environmental taxes (energy, transport, pollution, resources);
6. Ecologically regenerated surfaces.

The data will be analyzed both chronologically and thematically, and the interpretations will take into account the Romanian rural context, highlighting potential links between institutional efforts, economic involvement, and environmental outcomes.

a) Environmental protection expenditures by CAEN Rev.2 activities and types of expenditures

Between 2019 and 2023, total environmental protection expenditures in Romania recorded a significant increase. The most notable variations occurred in the category of non-specialized producers, where the budget doubled from 6,2 billion RON in 2019 to 12,3 billion RON in 2023. Budget allocations for environmental protection align with recent concerns regarding the need to make agricultural activity more sustainable, responsible, and inclusive (*Buzatu et al., 2024*). This trend reflects an accelerated effort to comply with environmental requirements by both public authorities and economic actors. According to a recent analysis on Romania and Serbia, the increase in environmental expenditures is primarily linked to *"compliance with European requirements on natural resource management and reduction of industrial impact"* (*Baicu, 2025*). The data confirm an increasingly active involvement of companies in sustainability-oriented actions, particularly in areas such as waste management, water protection, and biodiversity conservation, in line with the goals set through mandatory non-financial reporting (*Marcuta and Marcuta, 2023*).

Table 1

Environmental protection expenditure

Categories of producers	Categories of expenses	2019	2020	2021	2022	2023
CAEN Rev.2 (national economic activities)		**U.M.: Romanian lei (RON)**				
Non-specialized manufacturers	Overall	6,215,116,738	6,457,906,003	9,243,570,771	11,587,173,337	12,370,451,396
	Investments	1,174,524,016	1,109,705,175	1,098,533,154	1,638,688,273	2,575,561,994
	Added investments	589,514,813	296,133,799	340,817,185	518,817,064	747,836,425
	Integrated investments	585,009,203	813,571,376	757,715,969	1,119,871,209	1,827,725,569
	Current expenses	5,040,592,722	5,348,200,828	8,145,037,617	9,948,485,064	9,794,889,402
	Internal current expenditure	1,802,714,680	2,135,484,623	2,129,715,796	3,492,162,705	3,738,096,608
	External current expenditure	3,237,878,042	3,212,716,205	6,015,321,821	6,456,322,359	6,056,792,794
Specialized manufacturers	Overall	7,157,534,045	6,833,720,574	9,549,903,956	10,981,420,157	11,485,167,947
	Investments	446,792,998	517,928,132	859,788,338	1,247,652,730	1,089,519,009
	Current expenses	6,710,741,047	6,315,792,442	8,690,115,618	9,733,767,427	10,395,648,938

	Internal current expenditure	4,925,478,353	4,475,157,532	6,666,830,975	7,377,612,445	7,941,772,092
	External current expenditure	1,785,262,694	1,840,634,910	2,023,284,643	2,356,154,982	2,453,876,846
Public administration	Overall	9,207,400,001	7,111,400,000	8,239,633,391	9,085,802,232	7,651,860,100
	Investments	1,951,400,000	1,940,200,000	2,156,431,954	1,947,200,000	2,479,548,500
	Current expenses	3,068,800,000	3,670,300,000	3,896,799,999	4,141,202,232	4,794,431,000
	Internal current expenditure	1,436,860,329	1,511,569,601	1,784,729,724	1,739,390,873	1,565,505,992
	External current expenditure	1,631,939,671	2,158,730,399	2,112,070,275	2,401,811,359	3,228,925,008
	Grants awarded	4,187,200,001	1,500,900,000	2,186,401,438	2,997,400,000	377,880,600

(*NIS, http://statistici.insse.ro*)

Non-specialized producers

The share of investments in total expenditures remains relatively low. In 2023, investments represented only ~20% of the total, although they increased by more than 100% compared to 2019. A notable aspect is the growth of integrated investments (ecological technologies incorporated into current activities), which reached 1,82 billion lei in 2023, up from only 585 million in 2019 (a sign of a shift toward internal modernization).

Specialized producers

Current expenditures dominate, exceeding 10 billion lei in 2023, while investments slightly decreased compared to the previous year. This reliance on maintenance spending suggests an already mature infrastructure but with a slow pace of innovation.

Public administration

Presents the most balanced structure between investments and current expenditures. In 2023, investments reached 2,47 billion lei, while current expenditures amounted to 4,79 billion lei. The sharp drop in subsidies (from 4,18 billion lei in 2019 to only 377 million lei in 2023) suggests a reduction in direct support for local actors, especially those in rural areas. Risk management in agriculture requires continuous adaptation to climate and ecological conditions, including by directing investments toward sustainable practices (*Ghiuleanu et al., 2023*).

A critical aspect is the structure of current expenditures:

- For non-specialized producers, external expenditures are predominant (in 2023, these exceeded 6 billion lei, accounting for over 60% of total current spending).
- This dependence on suppliers and external services reduces the autonomy of local environmental systems and may affect long-term sustainability.

According to the FAO study, the outsourcing of environmental expenditures *"limits the strengthening of local capacities, especially in rural areas,"* and increases vulnerability to economic crises (*Baicu, 2025*).

The subsidies granted by public administration have undergone dramatic fluctuations:

- The drop from 2022 to 2023 was nearly 90%.
- This volatility directly affects ecological infrastructure projects in rural areas, where local authorities rely on these funds for modernization and compliance with environmental standards (*DEPARTAMENTUL PENTRU DEZVOLTARE DURABILĂ, 2025*).

b) Environmental protection expenditures by CAEN Rev.2 activities and environmental domains

The highest share of expenditures across all three producer categories was recorded in the field of waste management.

- Specialized producers consistently directed over 90% of their funds to this domain (in 2023, over 10,8 billion lei).
- Public administration and non-specialized producers significantly increased these expenditures in recent years, reaching 5,5 billion lei and 2,29 billion lei respectively in 2023.

This trend reflects European pressure to improve waste collection and treatment systems but also highlights the lack of balance in addressing other environmental areas (*Baicu, 2025*).

Table 2

Environmental protection expenditure by environmental domain

Categories of producers	Environmental areas	2019	2020	2021	2022	2023
CAEN Rev.2 (national economic activities)		U.M.: Romanian lei (RON)				
Non-specialized producers	Overall	6,215,116,738	6,457,806,003	9,243,470,771	11,587,173,337	12,370,331,396
	Air	2,168,630,589	1,884,344,742	3,981,833,292	3,537,165,709	3,715,009,802
	Water	1,387,310,473	1,607,606,361	1,727,353,075	2,498,181,031	3,096,213,865
	Waste	1,214,704,608	1,224,187,513	1,246,197,876	1,469,696,158	2,296,457,273
	Soil and groundwater	564,147,113	560,707,647	662,125,474	1,215,954,224	916,617,522
	Noise and vibration	9,253,560	15,079,724	13,486,756	73,140,661	66,042,668
	Natural resources and biodiversity	42,135,829	46,382,017	259,715,745	322,559,810	360,516,456
	Other domains	828,934,566	1,119,497,999	1,352,758,553	2,470,475,744	1,919,473,810
Specialized manufacturers	Overall	7,157,534,045	6,833,720,574	9,549,903,956	10,981,420,157	11,485,167,947
	Air	70,690,169	157,579,942	71,099,132	136,426,642	51,270,320
	Water	355,264,495	338,038,412	313,042,435	194,676,895	252,784,078
	Waste	6,543,553,723	6,056,315,603	8,950,597,234	10,446,873,985	10,899,914,500
	Soil and groundwater	159,880,780	143,465,697	195,785,204	83,342,573	141,397,593
	Noise and vibration	11,083	22,685	9241	41,387	27,121
	Natural resources and biodiversity	3,241,347	1,722,511	2,920,943	8,826,992	7,611,173
	Other domains	24,892,448	136,575,724	16,449,767	111,231,683	132,163,162
Public administration	Overall	9,207,400,001	7,111,400,000	8,239,633,391	9,085,802,232	7,651,860,100
	Air	2,408,084,900	775,392,820	1,127,824,543	921,589,322	205,267,777
	Water	1,830,800,000	1,711,500,000	1,862,800,000	1,531,100,000	1,563,700,000
	Waste	2,993,300,000	3,570,600,000	3,745,300,000	4,024,700,000	5,517,300,000
	Soil and groundwater	612,387,305	229,746,429	263,470,995	671,271,214	26,593,302
	Noise and vibration	507,479,419	117,630,712	238,587,838	399,587,404	71,837,096
	Natural resources and biodiversity	2,200,000	2,100,000	2,400,000	3,100,000	4,000,000
	Other domains	853,148,377	704,430,039	999,250,015	1,534,454,292	263,161,925

(*NIS, http://statistici.insse.ro*)

Air domain (significant decreases in the public sector)

Although initially high, expenditures for air protection have sharply decreased in the public sector, from 2,4 billion lei in 2019 to only 205 million lei in 2023. This decline is concerning in the context of increasing pollution from transport and industry in peri-urban rural areas (*EEA, 2023*). Investments in the water domain have significantly increased for non-specialized producers, from 1,38 billion lei in 2019 to 3,09 billion lei in 2023. This reflects initiatives to expand water and sewage networks in rural areas and aligns with the priorities set by the NRRP and LIOP (*MINISTRY OF INVESTMENTS AND EUROPEAN PROJECTS, 2024; MINISTRY OF ENVIRONMENT, WATERS AND FORESTS, 2022*).

Expenditures on biodiversity and natural resources remain low but have increased, especially among non-specialized producers (from 42 million lei in 2019 to 360 million lei in 2023). However, public administration allocates only symbolic amounts (less than 5 million lei/year), which reflects a lack of firm policy for the conservation of rural natural heritage (*WWF Romania, 2020*). Education is the backbone of a society committed to biodiversity conservation (*Buzatu et al., 2023*).

Spending on *"other domains"* (which may include climate change, ecological education, green IT) has significantly increased:

- From 828 million lei (2019) to 1,9 billion lei (2023) for non-specialized producers.
- Public administration recorded a decrease in this area, from 853 million lei (2019) to 263 million lei (2023), possibly due to the conclusion of projects with external funding.

The distribution of expenditures by environmental domains reveals an excessive concentration on waste management, to the detriment of other critical areas such as air, biodiversity, or noise. In rural areas, these imbalances translate into the absence of coherent multisectoral strategies for environmental protection and long-term sustainability (*Baicu, 2025; EEA, 2023*).

c) Environmental tax account by tax categories and CAEN Rev.2 activities

Taxes applied to energy consumption remain by far the main source of revenue from environmental taxes, ranging between ~18,7 and 21,3 billion lei annually.

- After a drop in 2020 (pandemic), the level of these taxes stabilized around 20 billion lei.
- This stagnation suggests a lack of green fiscal reform that would more actively stimulate the transition toward renewable energy sources (*OECD, 2024*).

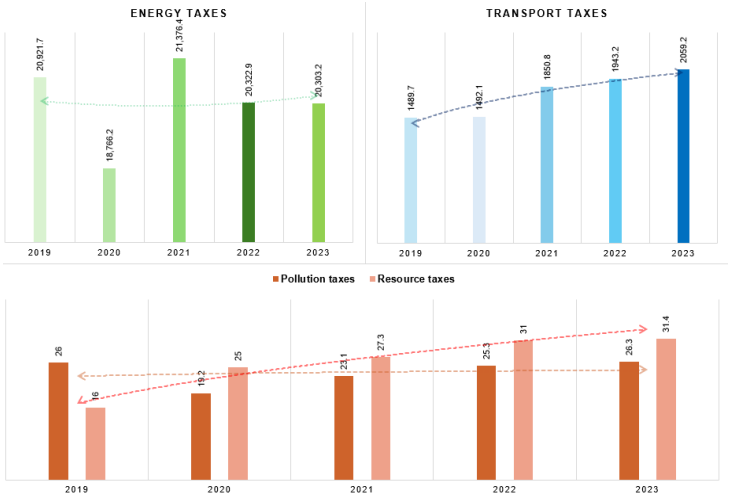

Fig. 1 - Multi-level chart representing the environmental tax account, U.M. = Millions of lei

(NIS, http://statistici.insse.ro)

The value of transport taxes increased by approximately 38% during the analyzed period:

- From 1,49 billion lei (2019) to 2,05 billion lei (2023).
- The growth is constant but still undersized compared to the actual environmental impact of transport (especially in rural areas), where individual transport dominates (*EEA, 2023*).

In the case of pollution taxes, values remain very low, below 30 million lei annually, with no notable variations.

- This reality confirms that the polluter does not truly pay in Romania (the system of penalties and direct pollution taxes is inefficient and outdated). The analysis of national statistical data aligns with global trends, where the effects of climate warming are already visible on agricultural yield, soil quality, and water resources, especially in vulnerable regions such as Dobrogea (*Buzatu et al., 2024*). The importance of soil conservation measures is also supported by recent studies highlighting the increased risks of degradation of Romania's agricultural land fund (*Buzatu et al., 2023*).

Looking at resource taxes, even though the values are small (from 16 million lei in 2019 to 31,4 million lei in 2023), the percentage increase is significant (almost double).

- It could reflect a modest tendency toward correcting the exploitation of natural resources, but the level is far too low to stimulate ecological responsibility in agriculture, forestry, or extraction.

The current structure of environmental taxes in Romania indicates a major dependence on energy-related taxes, while fiscal instruments with direct impact on pollution and resource exploitation are poorly developed. In rural areas, this fiscal imbalance limits the ability to influence sustainable behaviors and to finance the ecological transition.

d) Economy-environment material flow account

The volume of domestic extraction used was relatively constant in the early years, with a peak in 2021 (548 million tonnes), followed by a gradual decline to 526 million tonnes in 2023. This trend suggests a possible rationalization of resource extraction, either through optimization or a reduction in activity in some extractive sectors.

Table 3

Representative table showing the flow of material accounts

Material flows account indicators	2019	2020	2021	2022	2023
	U.M.: Tons				
Internal extractions utilized	524,545,306.59	534,345,855.17	548,315,247.55	540,803,253.59	526,765,855.16
Direct input of materials	579,780,898.9	588,943,787.28	609,794,431.45	600,452,030.82	580,300,436.61
Total material inputs	688,355,789.42	692,021,311.62	719,150,947.07	707,219,951.14	685,059,314.26
Internal consumption of materials	533,206,493.13	548,649,575.58	561,922,535.42	555,484,236.48	532,992,866.34
Physical balance of foreign trade	8,661,186.54	14,303,720.4	13,607,287.86	14,680,982.89	6,227,011.19

(*NIS, http://statistici.insse.ro*)

Total material inputs slightly increased until 2021 (719 million tonnes), then decreased to 685 million tonnes in 2023. This trend may reflect a higher interest in importing raw materials rather than local production (a typical phenomenon in economies that rely more on consumption and logistics than on domestic manufacturing). After an increase during 2019–2021, domestic material consumption slightly declined by 2023, reaching ~533 million tonnes, almost identical to the 2019 level. This indicates a stagnation in material efficiency, meaning the economy fails to produce more with fewer resources, an important sustainability indicator (*OECD, 2024*). The physical trade balance remains positive, indicating that Romania exports more than it imports, in terms of material mass.

- The highest value was recorded in 2022 (~14,7 million tonnes), but dropped to 6,2 million tonnes in 2023 – a sign of potential trade imbalances in raw materials.

The material flow account highlights an economy characterized by dependence on domestic extraction, inefficient material consumption, and volatility in resource trade. For rural areas, these figures reveal a lack of real progress toward a circular economy, where reuse and recycling should offset extraction.

e) Target 3 – Environment – DMC by material types (renewable and non-renewable)

Consumption of renewable materials declined sharply during the analyzed period:

- From 74,8 million tonnes (2019) to 52,8 million tonnes (2023), a reduction of approximately 30%.
- This trend goes against European sustainability goals and indicates an increasing dependence on non-renewable materials, with direct effects on rural areas, where agriculture, forestry, and renewable energy should predominate (EEA, 2024).

Table 4

DMC (Domestic Material Consumption) by resource type

DMC by material type	2019	2020	2021	2022	2023
	U.M.: Tons				
Overall	533,242,000.2	548,692,281.6	561,968,041.1	555,540,222.3	533,040,652.5
DMC from renewable materials	74,837,234.37	61,249,233.78	71,125,253.22	57,476,439.59	52,840,542.23
DMC from non-renewable materials	457,484,658.8	486,400,217.1	489,690,494	496,989,502.4	479,143,101

(*NIS, http://statistici.insse.ro*)

Consumption of non-renewable materials increased slightly until 2022, reaching ~497 million tonnes, then declined slightly in 2023. However, these materials consistently represented over 89% of total DMC, reflecting an economic structure based on:

- Minerals and construction materials;
- Fossil fuels;
- Non-recyclable industrial inputs.

In 2023, only 9.9% of total material consumption came from renewable sources – a rate well below the EU average of approximately 12–13%. Material consumption in Romania remains heavily oriented toward non-renewable resources, and the share of renewable materials is steadily decreasing. This imbalance highlights the lack of coherent policies on circular economy and green resources in rural areas. Without a clear corrective strategy, rural environmental sustainability is at risk.

f) Target 8 – Environment – Green space area by county

At the national level, an increase in green spaces is observed in several counties, but with uneven distribution and, in some cases, local regressions.

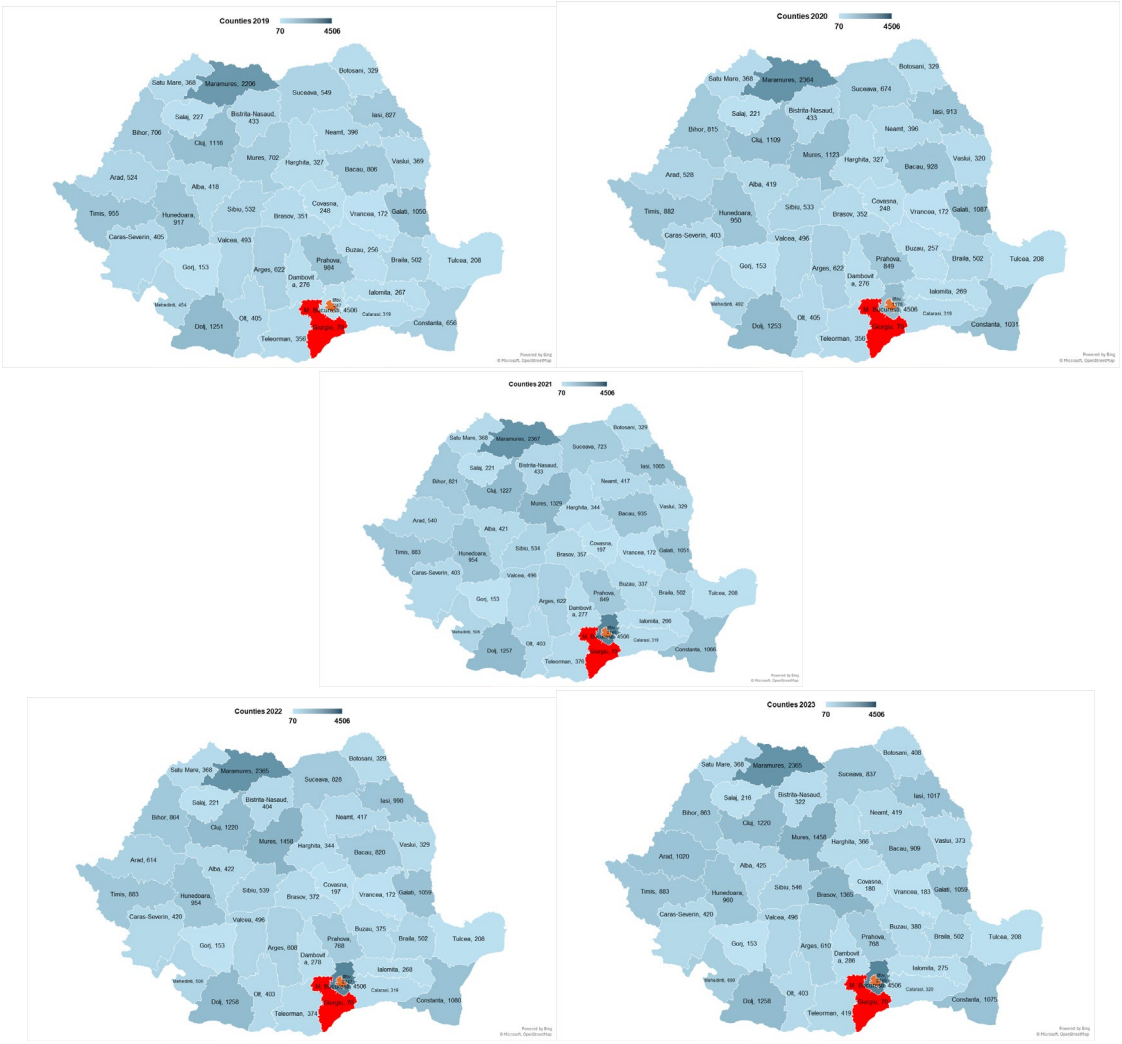

Fig. 2 - Collage of representative images showing the surface area of green spaces in Romania, U.M. = Hectares *(NIS, http://statistici.insse.ro)*

Some significant examples:

- **Counties with spectacular growth:**
  - *Ilfov*: from 247 ha (2019) to 2749 ha (2023), an increase of over 1000%, most likely due to ecological reconversion programs and green urbanization.
  - *Brașov*: from 351 ha to 1365 ha, a sustained evolution, possibly correlated with the development of ecological tourism and municipal projects.
- **Counties with stability or stagnation:**
  - *Bihor, Cluj, Galați, Sibiu*: slight positive variations, but no notable leaps.
  - *Dolj and Maramureș* maintain high levels (1258 ha and 2365 ha in 2023).
- **Counties with regressions:**
  - *Bistrița-Năsăud*: from 433 ha to 322 ha
  - *Covasna and Sălaj*: constant losses
  - These decreases may indicate urbanization pressure, lack of funds for redevelopment, or unbalanced logging not offset by replanting.

The Municipality of Bucharest maintains a constant declared green space area of 4506 ha. However, the lack of increase may hide a problematic reality in peripheral neighborhoods, where access to green spaces is unequal (*EEA, 2022*). In many counties with predominantly rural populations (e.g., Giurgiu, Teleorman, Vaslui), green space areas remain low and stagnant, affecting:

- ecological regeneration capacity,
- public health (access to nature),

- adaptation to climate change (shading, CO_2 capture).

This disparity shows that green policies are urban-focused, while rural areas remain underfunded for such green infrastructure. Green spaces in Romania show a generally positive evolution, but extremely uneven between counties. Rural areas are, in many cases, left behind, and the lack of intervention in these regions impacts local sustainability and resilience. Green space expansion programs should explicitly target rural communities.

g) Target 6 – Environment – Area of land undergoing regeneration by regeneration category

Natural regeneration represents the vast majority of ecological rehabilitation efforts, peaking in 2022 (19,781 ha) and slightly declining in 2023 (19,354 ha). This is a sustainable and low-cost practice, aligned with EU recommendations for forest habitat restoration (*European Commission, 2025*). The increase in naturally regenerated areas indicates a positive direction in reforestation and ecological conservation policies (*Buzatu et al., 2023*).

Table 5

Area of regenerated land (natural and artificial)

Regeneration by land type	Types of regeneration	2019	2020	2021	2022	2023
		U.M.: Hectares				
Regenerations - Total	Natural regeneration	16,016	17,162	15,904	19,781	19,354
	Artificial regeneration	8443	8027	8077	8200	7292
A. In forest fund - Total	Natural regeneration	16,016	17,162	15,898	19,781	19,350
	Artificial regeneration	8242	7921	7850	7984	7228
B. In land taken over by the forest fund - Total	Natural regeneration	0	0	6	0	4
	Artificial regeneration	72	20	36	168	34
C. On land outside the forest fund -Total	Natural regeneration	0	0	0	0	0
	Artificial regeneration	129	86	191	48	30

(*NIS, http://statistici.insse.ro*)

Artificially replanted areas decreased from 8443 ha (2019) to 7292 ha (2023). This reduction may be interpreted as:

- either a shift toward natural regeneration methods,
- or a decline in the operational capacity of forestry authorities due to lack of funding or personnel (*World Bank, 2025*).

Over 99% of both natural and artificial regeneration took place within the existing forest fund. Regeneration on reclaimed land or outside the forest fund remains insignificant (under 200 ha/year), indicating a lack of real forest expansion beyond already forested areas. For rural communities, these figures reflect:

- a lack of true expansion in afforested areas,
- but also a positive orientation toward natural ecological restoration.

Nevertheless, without additional investment in controlled artificial regeneration (especially on degraded or marginal lands), achieving a functional ecological balance in rural areas affected by past deforestation is not feasible (*Baicu, 2025*). Romania maintains a steady pace of forest regeneration, but without effectively expanding the national forest fund. The focus is on natural regeneration, which is sustainable but insufficient in light of the adaptation needs to climate change and increased rural resilience. The analysis of environmental spending, resource consumption, ecological taxation, and environmental interventions during the 2019–2023 period reveals notable progress in Romania's financial and institutional efforts toward environmental protection, but also highlights several structural dysfunctions that limit the actual impact in rural areas.

The increase in environmental protection expenditures, both from specialized producers and public administration, suggests a positive trend, especially through investments in waste management and water resource protection. However, the dominance of current expenditures over long-term investments, along with a reliance on external services, reflects a reactive rather than strategic nature of environmental policies.

On the fiscal side, environmental taxes are overwhelmingly dominated by energy consumption, while truly transformative tools (such as pollution or resource taxes) are marginal, ineffective, or symbolic. As such, current economic mechanisms do not sufficiently incentivize ecological behavior in rural areas. From a material consumption perspective, Romania remains heavily dependent on non-renewable resources, with

the share of renewables continuously decreasing (below 10% in 2023). This trend undermines the sustainability of local economic systems, especially in areas dominated by extractive industries.

Regarding natural capital (green spaces and ecological regeneration), data reflects a dual reality:

- On the one hand, some counties show spectacular increases in green space (e.g., Ilfov, Brașov),
- On the other hand, many rural areas remain underfunded or stagnant, with constant losses in green infrastructure. Furthermore, forest regeneration is almost exclusively limited to existing forests, without any real expansion of the national forest fund, which reduces the positive ecological impact in disadvantaged areas.

Romania has taken important steps toward environmental protection, but the results remain fragmented, reactive, and poorly aligned with the specific needs of rural areas. Without a strong shift toward strategic green investments, circular economy principles, coherent ecological taxation, and expansion of green infrastructure, the sustainable development of the rural environment remains a difficult objective to achieve.

S.W.O.T. analysis

The S.W.O.T. analysis provides an integrated view of Romania's ecological dynamics, with a focus on sustainable development in rural areas. Based on statistical data analyzed over the 2019–2023 period, this assessment highlights both favorable elements and structural vulnerabilities of current environmental policies and investments. In addition, it identifies strategic directions for action to enhance the efficiency and sustainability of the national environmental system.

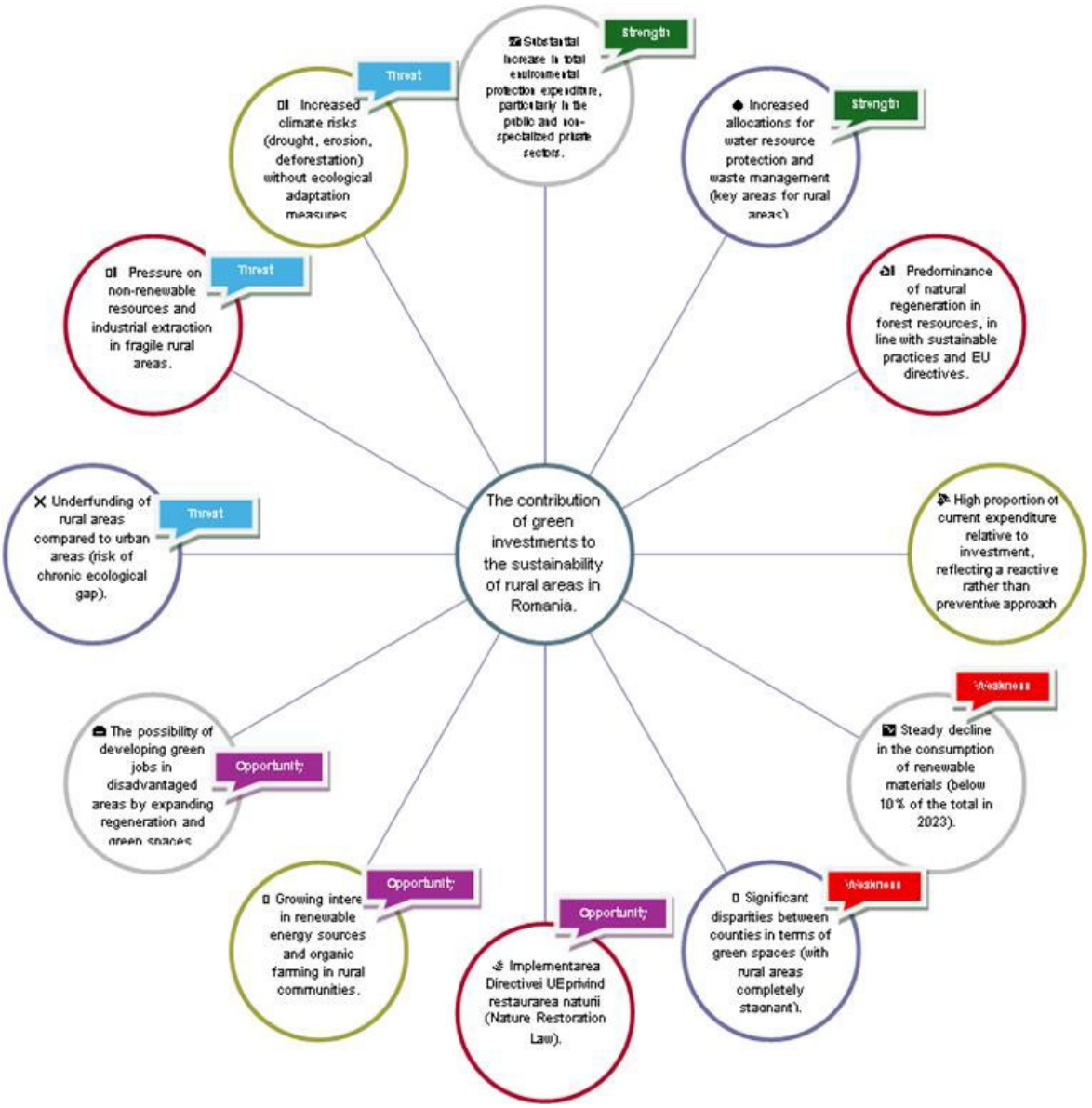

Fig. 3 - Representative SmartArt graphic with S.W.O.T. analysis

(Source: Own determination)

The assessment highlights a promising foundation for ecological action, but also the urgent need to rebalance priorities in favor of genuine sustainability in rural areas. For Romania to capitalize on its strengths and existing opportunities, it is essential to:

- Increase the share of green investments and reduce reliance on current expenditures.
- Expand green infrastructure and ecological regeneration beyond already forested areas.
- Strengthen fiscal mechanisms and support systems for rural communities.
- Integrate environmental policies with rural economic development (under a coherent, long-term vision).

CONCLUSIONS

The integrative analysis of statistical data on green investments, environmental protection expenditures, and resource use in Romania between 2019 and 2023 reflects a mixed dynamic regarding the ecological transition in rural areas. Although there is a notable increase in investments in green infrastructure and waste management (especially from non-specialized producers and public administration) imbalances persist across intervention domains and counties, as well as between preventive investments and those reacting to already existing environmental issues.

Current expenditures consistently exceeded capital investments, indicating a prioritization of maintaining and operating existing infrastructures over launching long-term sustainable initiatives. Financial allocations were predominantly focused on waste management and air protection, while resources dedicated to soil protection, biodiversity, or noise pollution remained significantly lower.

The environmental tax account revealed fiscal stability, yet with a very low share of pollution- and resource-specific taxes, suggesting limited potential of the current ecological taxation system to incentivize responsible behavior.

At the same time, the decline in domestic material consumption, along with the overall reduction in domestic extraction in 2023, can be interpreted either as a sign of moderate efficiency improvements or economic stagnation. Progress in expanding green areas in some counties and increased natural regeneration efforts show successful local initiatives, but remain insufficient at the national level.

Overall, the contribution of green investments to the sustainability of Romania's rural environment is visible, but fragmented. A more strategic, coherent, and balanced approach is needed (across sectors, regions, and types of expenditures) alongside deeper integration of circular economy principles and biodiversity conservation. Strengthening these directions could transform green investments into a central pillar of sustainable rural development.

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INTERPHASE TRANSPORTATION MECHANISMS IN AGRO-FOOD SYSTEMS AND THEIR IMPACT ON FOOD SAFETY

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MECANISME DE TRANSPORT INTERFAZIC ÎN SISTEMELE AGROALIMENTARE ȘI IMPACTUL LOR ASUPRA SIGURANȚEI ALIMENTARE

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ABSTRACT

This paper examines the fundamental role of interphase transport in agricultural systems and food processing technologies, emphasizing its significance for maintaining and improving food safety. Interphase transport refers to the physicochemical phenomena occurring at the boundaries between solid, liquid, and gaseous phases, which determine the mobility, transformation, and availability of substances within biological and technological environments. In agriculture, these processes influence nutrient uptake, the persistence and movement of contaminants in soil, water distribution in the root zone, and the activity of microbial communities essential for soil health. In the food industry, transport across phase boundaries governs heat and mass transfer operations, solute diffusion, moisture migration, and the behaviour of microorganisms embedded within complex matrices. The paper highlights how inadequate control of these mechanisms can lead to product instability, contamination, or reduced nutritional quality, while a deeper understanding enables the optimization of processing conditions and the design of safer production systems. By integrating current scientific knowledge and outlining recent advances, this study underscores the importance of interphase transport as a cross-cutting principle in ensuring food quality and safety across the entire agri-food chain.

REZUMAT

Această lucrare examinează rolul fundamental al transportului interfazic în sistemele agricole și tehnologiile de procesare a alimentelor, subliniind importanța sa pentru menținerea și îmbunătățirea siguranței alimentare. Transportul interfazic se referă la fenomenele fizico-chimice care au loc la limitele dintre fazele solidă, lichidă și gazoasă, care determină mobilitatea, transformarea și disponibilitatea substanțelor în mediile biologice și tehnologice. În agricultură, aceste procese influențează absorbția nutrienților, persistența și mișcarea contaminanților în sol, distribuția apei în zona radiculară și activitatea comunităților microbiene esențiale pentru sănătatea solului. În industria alimentară, transportul prin limitele de fază guvernează operațiunile de transfer de căldură și masă, difuzia solutului, migrarea umidității și comportamentul microorganismelor încorporate în matrici complexe. Lucrarea evidențiază modul în care un control inadecvat al acestor mecanisme poate duce la instabilitate a produsului, contaminare sau o calitate nutrițională redusă, în timp ce o înțelegere mai profundă permite optimizarea condițiilor de procesare și proiectarea unor sisteme de producție mai sigure. Prin integrarea cunoștințelor științifice actuale și sublinierea progreselor recente, acest studiu subliniază importanța transportului interfazic ca principiu transversal în asigurarea calității și siguranței alimentare pe întregul lanț agroalimentar.

INTRODUCTION

Interphase transport encompasses a series of physicochemical phenomena that occur at the boundaries separating solid, liquid, and gaseous phases, governing the transfer, transformation, and retention of substances within both biological systems and technological processes. In agricultural environments, these mechanisms influence the dynamics of nutrient uptake by plants, the mobility and persistence of soil contaminants, the distribution and retention of water in pedological structures, as well as the activity of microbial communities responsible for maintaining soil productivity. Within the food industry, interphase transport determines the behavior of solutes and gases during processing, dictates the efficiency

of heat and mass transfer operations, modulates the stability of dispersed systems, and affects the migration of volatile compounds and the survival of microorganisms embedded in complex food matrices.

As global demand for safe, high-quality food continues to rise, the study of transport phenomena occurring at phase boundaries becomes increasingly relevant for preventing contamination, optimizing technological operations, and designing production systems capable of meeting modern sustainability requirements. Processes such as the adsorption of toxic elements onto soil colloids, the penetration and transformation of pesticides on plant surfaces, oxygen diffusion during fermentative processes, or moisture migration in stored products exert direct influence on both food quality and consumer safety. A rigorous understanding of these mechanisms provides the foundation for improved management of critical control points along the agri-food supply chain and supports the development of advanced technologies grounded in the physicochemical behavior of multiphase systems.

This article aims to examine the role of interphase transport in agriculture and the food industry, assess its implications for ensuring food safety, and highlight contemporary research directions that contribute to enhancing product quality while reducing associated risks. Through an interdisciplinary approach that integrates concepts from materials science, agronomy, microbiology, and food engineering, the study offers a comprehensive perspective on a fundamental yet often underexplored determinant of global food security.

The technical means for internal transport are highly diverse, ranging from the simplest transport devices to the most advanced robots. All these technical means find their field of application. At the level of the national economy, these means achieve optimal applicability depending on the characteristics of the economic unit, the volume of goods handled, the variety and properties of the goods, etc.

Transport installations are stationary or mobile machines that carry loads in a continuous flow, in different directions, including vertically, covering through their design and dimensions the entire transport distance *(Brăcăcescu et al., 2014; Ciobanu et al., 2014; Dumitraşcu et al., 2020).*

It follows that any machine performing transport operations can be included in the category of transport installations (motor vehicles are not included in this category). Depending on their operating mode and construction system, transport installations are classified into:

- Continuous-action transport installations, with or without traction elements;
- Periodic-action transport means.

Continuous-action transport installations, regardless of their design, transport route, or the nature of the loads carried, are generally referred to as conveyors.

The main parameters used to assess transport installations are:

- Production capacity (the quantity of material transported per unit of time);
- The distance over which the transport is carried out;
- The route (for certain installations);
- The type of energy used for driving.

In the milling and baking industries, there are a number of specific activities whose definition is necessary and will be provided below:

- Internal (in-plant) transport represents the totality of activities through which raw materials, materials, semi-finished and prefabricated products, finished products, spare parts, etc., are moved within the production process between different work sections, storage areas, receiving or dispatch points, using specific means of transport *(Găgeanu et al., 2018; Milea et al., 2014*).
- Handling is a basic activity consisting of moving a load unit over short distances, within or near the workplace, with the purpose of supplying and clearing workstations, arranging goods in warehouses and control points, etc. Handling is performed mechanically, automatically, or robotically, using specific equipment, but also manually by workers (Păun et al., 2015; Păun et al., 2017).
- Storage is an important activity within internal transport technology and consists of keeping goods for a shorter period (temporary storage) or a longer period (effective storage), in covered or uncovered warehouses, at workplaces, or on loading/unloading platforms of economic units *(Păun et al., 2018; Mihai et al., 2018).*
- Loading and unloading are components of handling operations, adjacent to both internal transport and external transport activities. These consist of picking up, lifting, lowering, and placing goods at the required locations.

When establishing various interphase transport technologies in agriculture, milling, or the food industry, these technologies include various types of transport equipment: elevators, conveyors (horizontal, inclined, or vertical), screw conveyors, belt or chain conveyors, or pneumatic transport systems.

Figures 1 and 2 present two examples of technologies that use different types of conveyors *(Stroescu et al., 2019).*

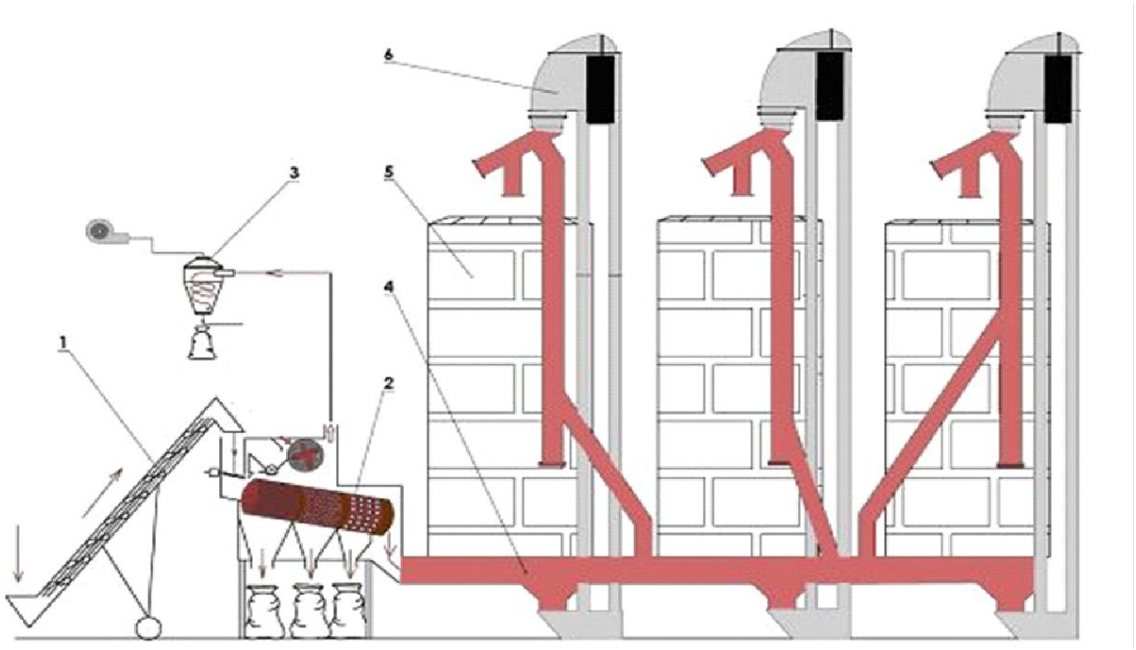

Fig. 1- Storage technology with a pre-cleaning and grain drying system.
(Stroescu et al., 2019)

The storage technology with a pre-cleaning and grain drying system is used in situations where drying is not carried out at the location where cereal or technical plant seeds will be stored. This technology consists of several dryers arranged in series, which are fed with pre-cleaned seeds by a single installation (a pre-cleaning module and a cylindrical seed cleaning unit – ICS type). The seeds are transferred cylindrically through a horizontal screw conveyor.

After drying, the seeds are discharged into transport vehicles (trailers) and carried to the reception base. Usually, this technology is applied mainly for warehouse storage.

The storage technology with a pre-cleaning and grain drying system involves the following technological operations:

1. Feeding the ICS installation with seeds using an inclined screw conveyor or a belt conveyor;
2. Pre-cleaning and sorting of seeds with the ICS seed cleaning installation;
3. Collection of impurities and dust by means of a cyclone or a battery of cyclones;
4. Feeding the dryers with pre-cleaned seeds using a horizontal screw conveyor;
5. Drying the seeds with a grain dryer;
6. Discharging the dried seeds and loading them into transport vehicles using a bucket elevator.

The pre-cleaning and sorting technology served as the basis for the development of the ICS seed cleaning installation.

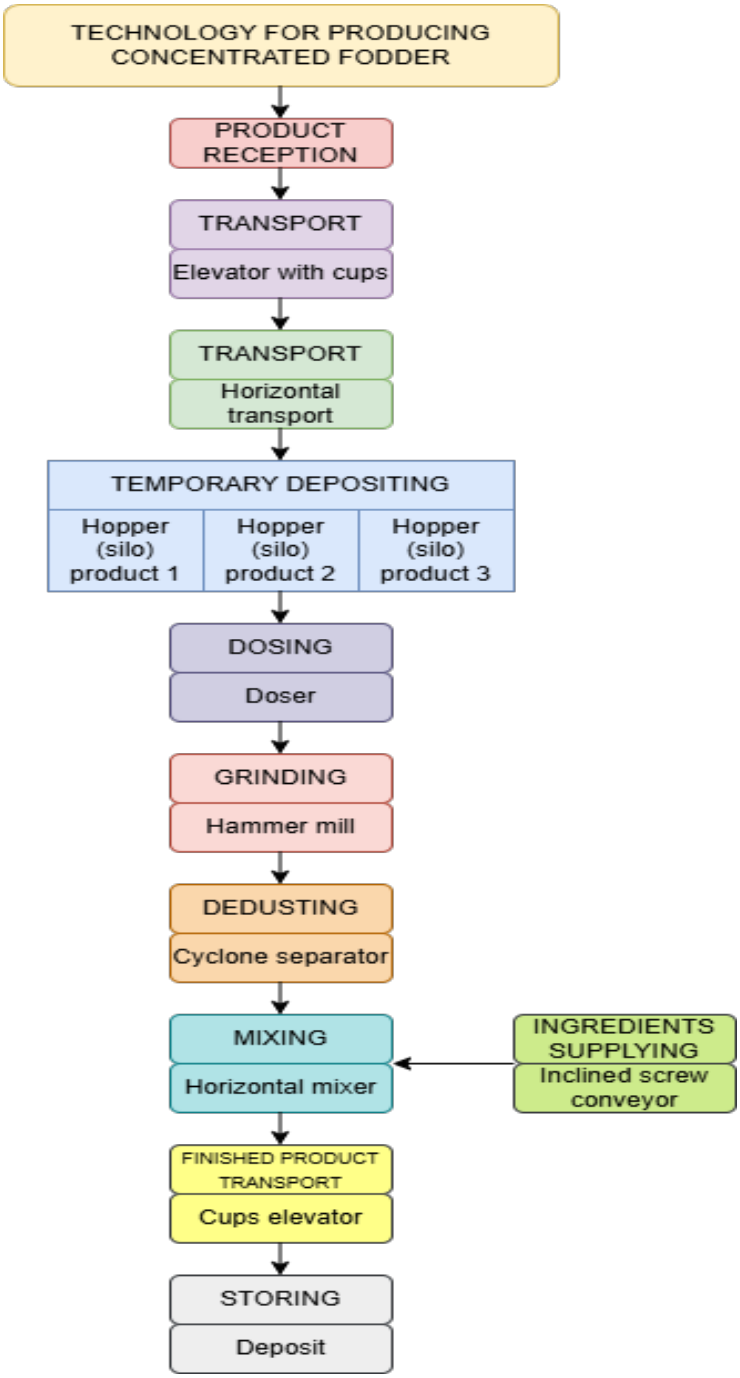

Fig. 2 - Technology for obtaining concentrated fodder.
(Păun et al., 2015; Păun et al., 2017; Păun et al., 2018)

MATERIALS AND METHODS

Bulk materials are characterized by a series of parameters: granulation, density, specific weight, angle of repose, and coefficient of internal friction. These materials consist of granules of various sizes, with each granule having an irregular shape defined by the dimensions of the circumscribed parallelepiped.

Knowing the characteristics of the materials to be transported is very important for selecting the appropriate type of equipment and determining its specifications. Below, we present several of the most commonly used machines in interphase transport.

Belt and bucket conveyors are efficiently used in grain silos as well as in the technological lines of the milling and baking industries (see Figure 3). Elevators can be classified according to the direction of transport (vertical or inclined), the traction element (belt or chain), the shape of the buckets (buckets with rounded bottoms or triangular-section buckets), the loading method (by scooping or pouring), and the unloading method (centrifugal or gravitational) *(Mihai et al., 2018).*

For the transport of bulk materials, bucket elevators are used, while for piece goods, swing-bucket elevators or elevators with rigid gripping devices are employed. Flexible traction elements used in elevators are rubber belts or chains, depending on the working conditions and the cost of the transport installation.

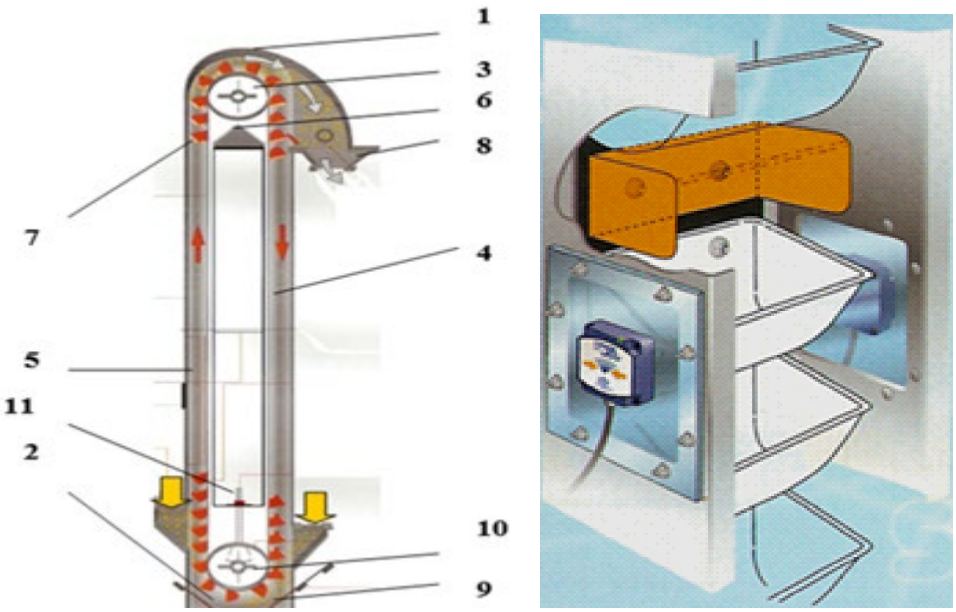

Fig. 3 - Bucket elevator.

1 – elevator head; 2 – elevator foot; 3 – drive unit; 4 – simple section; 5 – section with door and inspection window; 6 – non-return device; 7 – belt with buckets; 8 – head aspiration; 9 – magnetic separator; 10 – lower drum; 11 – belt tensioning device; (Stroescu et el., 2021)

Elevator transport capacity

The transport capacity Q of the elevator ranges between 2–300 t/h and can reach lifting (transport) heights of over 35 m, being determined by the following relation:

$$Q = 3{,}6\frac{i}{a}v.\gamma.\psi \quad , \text{ [t/h]} \tag{1}$$

Where :

i – capacity of one bucket, in liters (L);

a – bucket pitch, in meters (m);

v – elevator speed, in meters per second (m/s);

γ – bulk density of the product, in tons per cubic meter (t/m³);

ψ – bucket filling coefficient (when v = 1.25 m/s, ψ = 0.85).

Power required for elevator operation

The power required to drive the elevator is calculated using the following relation:

$$N_n = \frac{Q_e.H}{270\eta} \quad \text{, (CP)} \tag{2}$$

Where:

Ne – required driving power, in horsepower (HP);

Qe – transport capacity of the elevator, in tons per hour (t/h);

H – elevator height, in meters (m);

η – elevator efficiency (0.25–0.5).

Screw Conveyor

For horizontal transport, the screw conveyor is very frequently used. The screw conveyor consists of a closed or open trough (housing), or a cylindrical pipe, inside which a rotating screw moves granular, powdered, or other types of material (such as hay, chopped fodder, etc.).

The screw is made up of a shaft onto which a steel strip or flat bar is fixed (usually by welding) in the form of a helix (see Figure 4). During transport, the material is not carried into rotation due to its weight, frictional force, and centrifugal force.

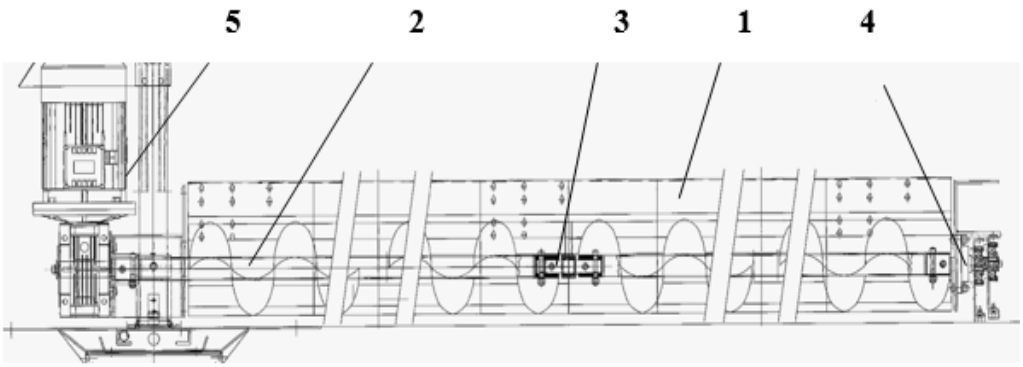

Fig. 4 - Horizontal screw conveyor
1 – housing; 2 – shaft with spiral;
3 – intermediate bearing; 4 – driven bearing; 5 – drive system;
(Nenciu at al., 2022)

High-speed screw conveyors can operate efficiently regardless of their inclination angle. In the case of slow-speed screw conveyors, the influence of centrifugal forces is negligible — the transported material being mainly under the action of gravity and friction forces.

In high-speed vertical screw conveyors, however, the transported material is primarily influenced by centrifugal forces. Due to these forces, the material particles are pushed away from the screw and pressed against the conveyor casing, forming concentric layers. During the conveying process, mixing of the material particles also occurs.

Calculation of transport capacity

The transport capacity of the equipment is determined using the following relation:

$$Q_s = \frac{\pi(D^2 - d^2)}{4} 60 pnc\gamma.\psi \tag{3}$$

Where:

- *Qs – transport capacity of the screw conveyor, in tons per hour (t/h);*
- *D – outer diameter of the screw, in meters (m);*
- *p – screw pitch, in meters (m);*
- *n – screw shaft speed, in revolutions per minute (rpm), with K = 60, 45, or 30;*
- *c – reduction coefficient of productivity depending on the screw inclination angle;*
- *γ – bulk density (hectoliter mass) of the transported product, in tons per cubic meter (t/m³);*
- *ψ – filling coefficient: 0.3–0.5;*
- *d – shaft diameter, in meters (m).*

Calculation of Required Power

The power required to drive horizontal and inclined screw conveyors (up to a 20° inclination angle) is calculated using the following relation:

$$N = \frac{Q}{367}(L_0 w_0 + H) \tag{4}$$

Where:

N – power required to drive the screw conveyor, in kilowatts (kW);
Q – transport capacity, in tons per hour (t/h);
H – lifting height of the material, in meters (m);
L_0 – horizontal projection of the material travel distance, in meters (m);
w_0 – experimental coefficient of resistance to material movement inside the trough; for grains, w_0 = 1.2.

For screw conveyors with inclination angles between 20° and 45°, the power required for operation can be calculated using the following relation:

$$N = \frac{Q}{367}(L_0 w_0 + H)\eta \text{ ,(kW)} \tag{5}$$

Where:

η – correction coefficient depending on the inclination angle of the screw.

Belt Conveyor

Belt conveyors (Figure 5) are continuous transport installations with wide applicability in industries such as the aggregates industry, the food industry, the mining industry, the transport sector, and recycling.

Belt conveyors are the most widely used type of conveyor and can be employed in numerous handling processes within production units, warehouses, and loading–unloading areas. They are capable of moving both bulk materials (such as grain, ground products, sawdust) and piece goods (such as bags, packages, and crates).

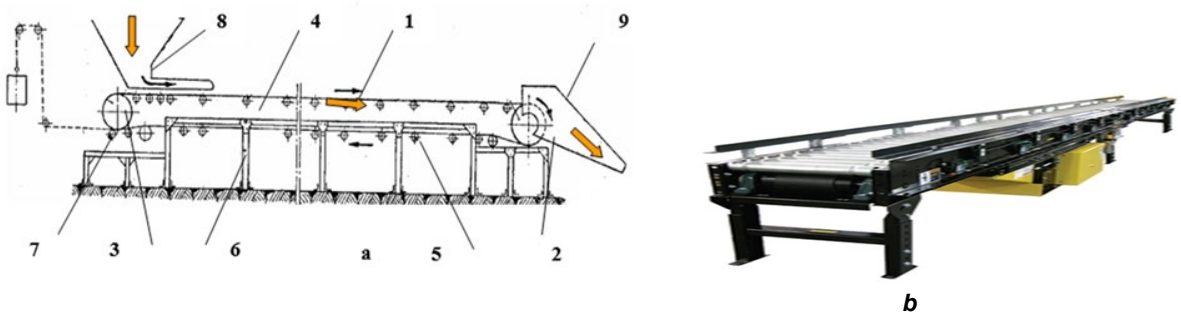

Fig. 5 - Belt Conveyor.

a – sketch; b – general view

1 – belt; 2 and 3 – drums; 4 and 5 – support rollers; 6 – metal frame; 7 – belt tensioning device; 8 – feed hopper; 9 – discharge hopper

(Nenciu at al., 2022)

Classification of Belt Conveyors

- By construction type: stationary or movable;
- By the direction of material movement: horizontal or inclined;
- By route length:
  - Short: with the loaded branch of the belt horizontal or at a constant inclination;
  - Long: for standard constructions, the length is limited to 250–300 m.

The transport route follows the profile of the usage location and can include one or more conveyors.

Stationary conveyors are used in warehouses, work sections, or between them, generally combined with other conveyors or handling systems.

Movable conveyors are built and adapted according to needs and, compared to stationary conveyors, offer additional mobility and the possibility of adjusting the material transport height. This is achieved by rotating the upper part of the metal frame up or down around a pivot. Movable conveyors can also be used for additional purposes, such as feeding multiple bunkers at various work points.

The belt conveyor consists of an endless belt (Figure 5) that rotates around two drums. The belt is supported by several carrying rollers.

Calculation of Transport Capacity

The transport capacity of belt conveyors is determined by the following relation:

$$Q = 3{,}6.q.v = 576.B^2.\gamma.v.tg\rho_1, \quad [\text{t/h}] \tag{6}$$

Where:

Q – transport capacity, in tons per hour (t/h);

$$q = S = \frac{bh}{2} = 0{,}16B^2.tg\rho_1, \quad [\text{t/m}] \tag{7}$$

q – weight of material per meter of belt, in t/m:

B – belt width, in meters (m);

γ – bulk density of the transported product, in t/m³;

v – belt speed, in meters per second (m/s);

ρ_1 – natural angle of repose, in degrees;

b = 0.8 B – width of the material layer on the belt, in meters (m);

h – height of the material layer on the belt, in meters (m);

$$h = 0{,}5\ b\ tg\ \rho_1 = 0{,}4\ B\ tg\ \rho_1 \tag{8}$$

For inclined belt conveyors, the transport capacity is calculated as:

$$Q = 3{,}6.q.v = 576.B^2.\gamma.v.tg\rho_1.\beta \text{ [t/h]} \quad (9)$$

Where β is the correction coefficient

Pneumatic transport

Pneumatic transport (Figure 6) refers to the movement of materials in powdered or granular form using a gas stream through a hermetically sealed piping system. From an aerodynamic perspective, transport in air currents is a typical case of two-phase flow, where the transporting agent (usually air) is the gaseous phase, and the transported agent (material particles) is the solid phase.

Unlike classical pneumatic transport, pneumatic transport of flour raises more challenging issues regarding sealing and surface finish of components that slide against each other, such as gates, distributors, and nozzles.

The conveying velocity in the pipeline is 3–5 m/s, and the working pressure is 0.35–1.4 bar. The compressed air source is usually a compressor.

Along the transport pipe, up to the first nozzle, the following are installed:

- A safety valve to prevent overpressure;
- A pressure gauge;
- A check valve to prevent flour from being pushed back into the system in case of residual material when the compressor stops.

Therefore, it is recommended to run the system empty for 1 minute before shutting down the installation.

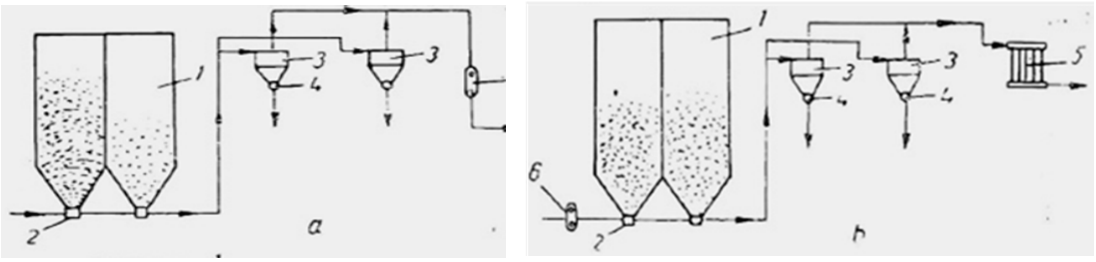

Fig. 6 - Technological scheme of a pneumatic flour transport installation.
a – flour transport by suction; b – flour transport by pressure;
1 – flour cells; 2 – flour feeder; 3 – cyclone; 4 – rotary airlock; 5 – filter; 6 – compressor
(Nenciu at al., 2022)

The calculation for pneumatic transport is performed after determining:

- The required transport routes;
- The quantity of product to be transported per hour;
- The number of routes;
- The length of each pipe, in meters.

In Figure 7, a system for producing concentrated feed is shown, which includes a bucket elevator, a horizontal screw conveyor with three discharge outlets, pneumatic transport of the ground product, an inclined screw conveyor.

Fig. 7 - Concentrated Feed Production Installation with bucket elevator, horizontal screw conveyor with three discharge outlets (TEO), pneumatic transport, inclined screw conveyor (TEI 110)
(Stroescu et al., 2021)

RESULTS

The findings of this study highlight the central role of transport phenomena occurring between solid, liquid, and gaseous phases in determining the functional stability, quality, and safety of agro-food products *(Nenciu at al., 2022).* The results indicate that the efficiency of nutrient transfer in agricultural systems is strongly influenced by the physicochemical characteristics of phase boundaries, particularly in soils with variable texture, porosity, and organic matter content. These interactions dictate not only the availability of essential elements for plant uptake but also the mobility of contaminants that pose a risk to food safety *(Stan (Tudora) et al., 2022; Oprescu et al., 2023; Vlăduț et al., 2023).* In technological processes specific to the food industry, transport across phase boundaries governs the rate of mass and heat transfer, which in turn affects product consistency, microbial dynamics, and the preservation of bioactive compounds. The study suggests that inadequate control of these mechanisms can lead to unstable dispersions, reduced diffusivity of key components, and increased susceptibility to microbial contamination *(Cujbescu et al., 2023; Tăbărașu et al., 2024)*.

The analysis further demonstrates that optimizing conditions at phase boundaries—whether through soil amendments, controlled hydration regimes, or improved processing parameters—can significantly enhance both productivity and safety outcomes. Notably, emerging technologies such as membrane separation systems, micro- and nano-structured carriers, and advanced drying techniques offer new avenues for manipulating interphase transport with greater precision. However, their successful implementation requires a more comprehensive understanding of the molecular interactions governing transport resistance and kinetic limitations. Future research should therefore focus on multiscale modeling approaches capable of linking microscale physicochemical interactions with macroscale system performance. Additionally, integrating real-time monitoring tools into production systems may allow dynamic adjustment of transport-related parameters, ultimately contributing to more robust and safer agro-food chains.

Using the installation shown in Figure 7, a series of experiments were carried out, as presented below. Tables 1 and 2 show the results obtained from experiments using the simple bucket elevator ES 100.

Table 1

Measurement Sheet – Parameters during Operation under Load

No.	Characteristic	Unit	P.I	P.II	P.III	Average	Remarks
0	1	2	3	4	5	6	7
1	Transport capacity	kg/h	4390.2	5710.6	6003.8	5368.2	sunflower
			8379.2	10453.2	11210.5	10014.3	wheat
			7221.6	9379.1	10235.4	8945.4	corn
2	Sample mass	kg	73.2	95.2	100.1	89.5	sunflower
			139.7	174.22	186.8	166.9	wheat
			120.4	156.3	170.6	149.1	corn
3	Sample duration	s	60	60	60	60	-
4	Upper drum speed	rot/min	107	107	107	107	-
5	Lower drum speed	rot/min	107	107	107	107	-
6	Supply voltage	V	380	379	380	380	sunflower
7	Current absorbed	A	3.9	3.8	3.9	3.9	
8	Power absorbed	kW	1.38	1.35	1.38	1.37	
9	Energy consumed	kWh	0.02	0.02	0.02	0.02	
10	Supply voltage	V	379	380	380	380	wheat

11	Current absorbed	A	4.0	3.9	3.9	3.9	
12	Power absorbed	kW	1.42	1.38	1.38	1.40	
13	Energy consumed	kWh	0.02	0.02	0.02	0.02	
14	Supply voltage	V	378	378	378	378	corn
15	Current absorbed	A	4.0	4.1	4.0	4.0	
16	Power absorbed	kW	1.41	1.45	1.41	1.42	
17	Energy consumed	kWh	0.02	0.02	0.02	0.02	
18	Speed of cup band	m/s	2.20	2.20	2.20	2.20	
19	Specific electrical power consumption	kWh/t	0.46	0.35	0.33	0.38	sunflower
			0.24	0.19	0.18	0.20	wheat
			0.28	0.21	0.20	0.23	corn

Nominal Characteristics of Elevator Motor ES100: Motor type AT 100L 28-6, Pn = 1.5 kW, n = 940 rot/min

In = 4.2 A, η = 0.75, cos φ = 0.72

Table 2

Summary Sheet – Qualitative and functional parameters under load

Nr. crt	Determined parameter	Unit	Parameter value		Remarks
			Theoretical value	Measured value	
0	1	2	3	4	5
1	Motor's nominal rotation frequency	rot/min	940	938.67	-
2	Training drum rotational frequency	rot/min	107	107	-
3	Belt speed with cups	m/s	2.25	2.20	
4	Transport capacity of cereals	kg/h	3000-6000	5368.2	sunflower
				10014.3	wheat
				8945.4	corn
5	Output power	kW	1.5	1.49	-
6	Absorbed power	kW	-	1.37	sunflower
7	Consumed electrical energy	kWh	-	0.02	
8	Specific electric energy consumption	kWh/t	-	0.38	
9	Absorbed power	kW	-	1.40	wheat
10	Consumed electrical energy	kWh	-	0.02	
11	Specific electric energy consumption	kWh/t	-	0.2	

12	Absorbed power	kW	-	1.42	corn
13	Consumed electrical energy	kWh	-	0.02	
14	Specific electric energy consumption	kWh/t	-	0.23	

CONCLUSIONS

The elevator is a demanding machine from the point of view of maintenance and repairs, since it is a machine that has in its components many parts in motion, parts which misalign or wear out to a large extent. Wear and misalignment appear due to the fact that this machine works at height and the centering of the belt is rather difficult. In the situation when misalignment of the belt with buckets occurs, frictions and abnormal noises appear in the operation of the elevator. This misalignment appears when slackening of the belt with buckets occurs or a partial rupture of the belt occurs as a result of improper adjustment of the tensioning device. For the elimination of these misalignments, the elevator must undergo daily inspection and control. Since a lot of dust develops inside the elevator, it is necessary to check and ensure perfect sealing and suction in the working process. In operation, the grain flow must be in close accordance with the transport capacity because overloading leads to clogging and blocking of the belt with buckets if the motor is not provided with a disengagement device.

High-speed screw conveyors can operate in good conditions regardless of their inclination angle. In the case of slow screw conveyors, the influence of centrifugal forces is neglected, the transported material being under the action of weight and friction forces. In the case of high-speed vertical screw conveyors, the transported material is acted upon especially by centrifugal forces. At low speeds, the integrity of the material is satisfactorily maintained, but as speed increases, the degree of damage increases, limiting the field of use mostly to cereals intended for feeding. The noise is sufficiently pronounced, and dust formation is accentuated in the discharge area. Adaptability and universality are satisfactory, and the criteria regarding the working and maneuvering area are average. The energy requirement is low to medium.

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INNOVATIVE TECHNOLOGIES FOR THE SUSTAINABLE DEVELOPMENT OF FRUIT GROWING: ECONOMIC, SOCIAL AND ENVIRONMENTAL IMPACTS
/
CONTRIBUȚIA TEHNOLOGIILOR INOVATIVE LA DEZVOLTAREA DURABILĂ A POMICULTURII: IMPACT ECONOMIC, SOCIAL ŞI ECOLOGIC

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ABSTRACT

The paper addresses the impact of innovative technologies for the maintenance of fruit plantations on the sustainable development of the horticultural sector, considering their economic, social, and ecological components. The research was carried out at INMA Bucharest through a testing and evaluation program for technical systems designed for orchard maintenance operations, including the root pruning equipment (ETR), the inflorescence thinning equipment (ERI), and the orchard working platform (PP). The results revealed a significant improvement in the economic efficiency of maintenance operations by reducing fuel consumption, operating time, and overall operating costs. From a social perspective, the use of innovative equipment contributes to increased operator safety and comfort, reduced physical effort, and optimized work processes. From an environmental point of view, positive effects were observed through reduced soil compaction and decreased pollutant emissions. The study concludes that, the integration of these innovative technologies into the mechanization system of fruit growing, represents a key direction for achieving the sustainable development goals within modern fruit farms.

REZUMAT

Lucrarea abordează impactul tehnologiilor inovative de întreținere a plantațiilor pomicole asupra dezvoltării durabile a sectorului horticol prin prisma componentelor economice, sociale și ecologice. Cercetările au fost realizate în cadrul INMA București printr-un program de testare și evaluare a sistemelor tehnice destinate lucrărilor de întreținere în livezi, incluzând echipamentul pentru tăierea rădăcinilor (ETR), echipamentul pentru rărirea inflorescențelor (ERI) și platforma pomicolă (PP). Rezultatele obținute au evidențiat o îmbunătățire semnificativă a eficienței economice a lucrărilor prin reducerea consumului de combustibil, a timpilor de operare și a costurilor de exploatare. Însă din perspectivă socială, utilizarea echipamentelor inovative contribuie la creșterea siguranței și confortului operatorilor, reducerea efortului fizic și optimizarea proceselor de muncă. Pe plan ecologic, s-au constatat efecte pozitive prin diminuarea gradului de compactare a solului și reducerea emisiilor poluante. Concluziile studiului confirmă că, integrarea acestor tehnologii inovative în sistemul de mecanizare a pomiculturii, reprezintă o direcție esențială pentru atingerea obiectivelor de dezvoltare durabilă la nivelul exploatațiilor agricole moderne.

INTRODUCTION

In the current context of modern agriculture, the sustainable development of fruit growing is a strategic priority, given the need to increase economic efficiency, reduce environmental impact and improve working conditions for operators. The mechanization of technological processes in orchards has evolved significantly in the last decade, through the introduction of innovative equipment designed to ensure a high level of precision, safety and sustainability.

Within the National Strategic Plan 2023–2027, fruit growing is considered a priority area of Romanian agriculture, promoting the transition to sustainable practices by introducing innovative mechanization and automation technologies. These aim to increase productivity, reduce production costs and reduce the impact on the environment, while improving the working conditions of operators. The

document emphasizes the importance of technology transfer between the research environment and farmers, through partnership projects and through the training of skills in the field of precision agriculture and the digitalization of agricultural processes (*Government of Romania*, 2023).

In line with the European objectives set by the European Green Deal and the "Farm to Fork" Strategy, Romania has undertaken, through the National Strategy for Sustainable Development 2030, to promote a model of smart and resilient agriculture, based on innovation, energy efficiency and the protection of natural resources. The strategic document "*RNV Romania 2023* " highlights the major directions of action in the agri-food sector, which aim to increase the competitiveness of the sector, reduce carbon emissions, support local production and increase the standard of living in rural areas (*Ministry of Agriculture and Rural Development*, 2023).

The development of the Voluntary National Report (VNR) was a broad, participatory and multi-sectoral process, but the review process involved representatives of public institutions, academia, the private sector, non-governmental organizations and civil society, reflecting a collective effort to integrate sustainability principles into national policies.

The assessment of the degree of achievement of the 17 Sustainable Development Goals (SDGs) was carried out based on national indicators monitored since 2016, revealing a level of achievement of 62.1%, according to data from the National Institute of Statistics. Favorable results were recorded in areas such as poverty reduction, increasing the share of renewable energy and reducing greenhouse gas emissions, but major challenges persist regarding quality education (SDG 4), sustainable management of water resources (SDG 6) and responsible consumption (SDG 12), Fig.1. Overall, the RNV emphasizes the need to accelerate national efforts to achieve sustainable development targets and strengthen society's resilience to crises.

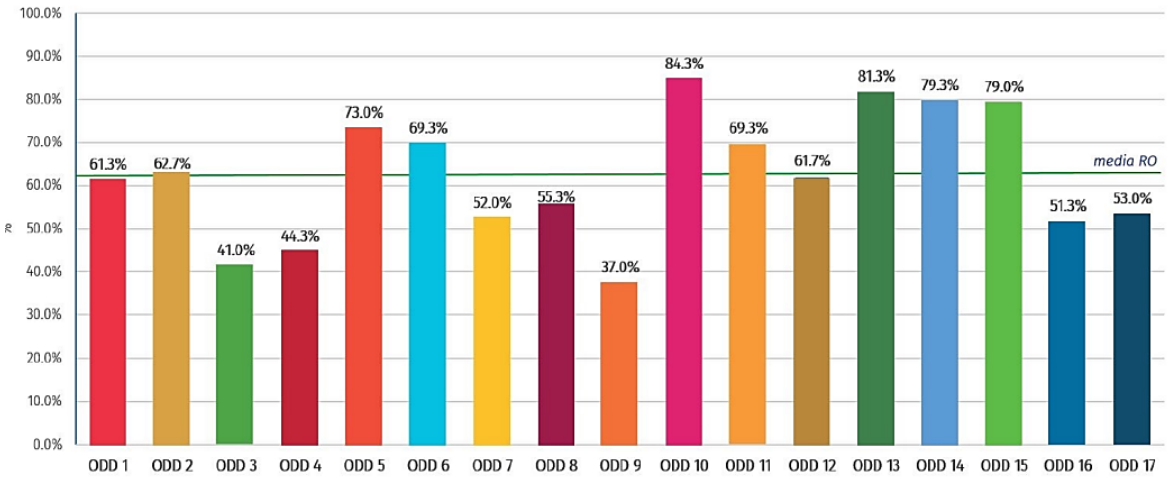

Fig. 1 - Implementation of the 17 SDGs in Romania

In addition, the European Union's requirements for the transition to a green economy and the implementation of the "*Farm to Fork*" principles require the adoption of low-carbon technologies capable of simultaneously meeting the objectives of productivity, environmental protection and social responsibility. The European "*Farm to Fork*" strategy is one of the main pillars of the European Green Deal, adopted by the European Commission in 2020, with the objective of transforming the European agri-food system into a fair, healthy and environmentally friendly one (*European Commission*, 2020).

This strategy aims to ensure a balance between agricultural productivity, environmental protection and social well-being, by reducing the ecological footprint of agriculture and promoting sustainable food production practices (*European Parliament*, 2025).

The implementation of innovative technologies in fruit growing generates a series of complex effects, with a direct impact on the economic and social development of fruit farms. The mechanization of maintenance and harvesting works optimizes production costs by reducing the consumption of material and energy resources, increasing labor productivity and decreasing work execution times. At the same time, the use of modern equipment contributes to the economic stability of fruit farms, allowing for more efficient planning of activities, reducing losses and increasing the quality of the production obtained.

The purpose of this paper is to analyze the contribution of innovative orchard maintenance technologies to the sustainable development of the sector, by evaluating their economic, social and ecological impact, in relation to conventional practices.

MATERIAL AND METHOD

In the context of modern fruit growing, which encourages the adoption of innovative, energy-efficient and environmentally friendly technologies, they can contribute to: reducing the consumption of pesticides and chemical fertilizers; reducing carbon emissions and fossil fuel consumption; preserving biodiversity and soil fertility; increasing food quality and safety; digitizing and monitoring technological processes in agricultural holdings.

Modern technologies, such as the root cutting equipment - ETR, the inflorescence thinning equipment - ERI and the fruit platform - PP, contribute to the optimization of maintenance and harvesting works, reducing the dependence on manual labor and ensuring a superior uniformity of interventions. These technical systems, designed on principles of innovation and energy efficiency, allow for sustainable resource management and better adaptation to the variable conditions in fruit farms.

The implementation of these innovative technologies represents not only a technical solution for the modernization of fruit growing, but also a concrete step towards achieving the targets imposed by the European Union for climate neutrality by 2050. At the same time, their adoption supports sustainable rural development, by strengthening the competitiveness of farms, creating jobs and increasing the economic resilience of horticultural holdings.

The sustainable development of Romanian fruit growing is closely linked to the integration of research and innovation into production systems. The National Strategy for Research, Innovation and Smart Specialization (SNCSII 2022–2027) promotes the valorization of scientific results through technological solutions directly applicable in fruit farms. These initiatives aim to stimulate sustainable mechanization, the use of smart sensors, the automation of works and the application of monitoring systems to optimize resources (water, energy, nutritional inputs).

On the social level, the need to train a new generation of specialists in the fruit growing field, capable of implementing modern technologies and managing integrated production systems, is highlighted, thus contributing to reducing the emigration of young people from rural areas and strengthening local agricultural communities. At the same time, national strategic documents promote social inclusion and the creation of stable jobs in rural areas by expanding family farms and fruit growing cooperatives.

From an ecological perspective, Romania is pursuing a transition to circular agriculture, based on the conservation of natural resources, the reduction of food waste and the limitation of the use of phytosanitary products. Support programs for local Global GAP certified producers, promoted by large retailers in partnership with research institutions, demonstrate the practical applicability of the "Farm to Fork" principles at the national level, by developing short, safe and traceable food chains. Thus, the integration of innovative technologies into the national fruit-growing system represents not only a direction of technological modernization, but also an essential condition for achieving the European objectives regarding sustainable development by 2030, simultaneously contributing to increasing economic competitiveness, protecting the environment and strengthening social cohesion in the Romanian rural area. In the current context of the transition towards smart and sustainable agriculture, Romania is increasingly aligning with European and global trends regarding the integration of innovative technologies in fruit growing. Community strategies are intensely promoting smart mechanization, digitalization and reducing the ecological impact of agricultural activities. In this framework, Romanian research, represented by specialized institutions such as the National Institute of Agricultural Machinery (INMA) Bucharest, has focused its efforts on developing modern equipment, experimental models adapted to local specifics, but compatible with European technological standards (Fig.2, Fig.4, Fig.6). The research was carried out during 2024–2025, aiming to evaluate the technical and functional performances of innovative equipment intended for maintenance work in fruit plantations.

The study tested three pieces of equipment, experimental model (EM), components of the innovative technology for maintaining fruit plantations:

- ETR – *Equipment for cutting tree roots* , intended for maintenance work on the root system in order to stimulate regeneration and control growth vigor. The equipment works in conjunction with the tractor, being hydraulically operated and equipped with a cutting force monitoring system.

- ERI – *Inflorescence thinning equipment* , designed for the mechanized operation of reducing the number of flowers, with the aim of improving production quality and fruit uniformity.
- PP – *Fruit platform* , used for cutting, phytosanitary treatments and harvesting, equipped with a hydraulic lifting system, tilt sensors and safety modules for operators.

Technologies developed at the national level – such as the projects of the root cutting equipment (ETR-0, Fig.3), the inflorescence thinning equipment (ERI-0, Fig.5) and the fruit platform (PP-0, Fig.7) – fit perfectly into the directions promoted by these strategies. They were designed and built based on the principles of sustainable engineering, with an emphasis on energy efficiency, reducing resource consumption and increasing the quality of agricultural work. At the same time, these innovations contribute to improving working conditions, increasing the competitiveness of fruit farms and reducing the carbon footprint of production processes.

Fig. 2 - Equipment for cutting roots, *AGROFER* company from Italy

Fig. 3 - Technical equipment for cutting tree roots, ETR-0, 3D design

Fig. 4 - *Darwin* flower thinning machine

Fig. 5 - Thinning equipment inflorescence in trees, ERI-0, 3D project

Fig. 6 - *Agri* model platform *Jupianti*

Fig. 7 - Experimental model Platform for fruit growing, PP-0, 3D project

The tests were carried out in the apple and plum orchards of INMA Bucharest, on reddish-brown soils with a loamy texture. The fruit species studied were the *Idared* and *Golden Reinders varieties* , which were in fruiting stage.

The parameters determined to characterize the equipment performance were the following indicators:

1. Technical and functional parameters: working speed, intervention depth, cutting force, working capacity, stability of the equipment in operation.
2. Economic parameters: specific fuel consumption (l/ha), unit cost of work (lei/ha), resource utilization efficiency.

3. Social parameters: operator comfort, noise level, degree of physical strain, operating safety.
4. Ecological parameters: degree of soil compaction, indirect pollutant emissions, soil losses and impact on soil biostructure in the work area.

The evaluation methodology shows how experimental determinations were carried out through direct measurements, based on standardized procedures for testing agricultural machinery, correlated with economic evaluations and comparative analyses compared to manual or semi-mechanized work.

Operational efficiency is reflected in how much each piece of equipment reduces time and manual labor, expressed in hours/ha and a substantial annual saving. The agronomic effect is revealed by the mechanisms of the equipment, selective inflorescence thinning (ERI) can increase fruit mass and uniformity, but may reduce total yield; root pruning (ETR) can regulate vegetation and influence ripening (*Tahir Khurshid and GP Sanderson*, 2023). However, limitations are generated by seasonality, soil limitations, tree size, acquisition cost, short-term tests versus long-term effects.

At the methodological level, the research aimed at adopting and adapting European good practices in the field of fruit growing mechanization, by studying existing solutions in countries with tradition and innovation in the sector – such as Italy, France, Germany and Spain. In these countries, mechanized pruning, thinning and maintenance systems for fruit trees have demonstrated a significant increase in operational efficiency and a reduction in production costs. Romania, through INMA and its partners from the academic and private sectors, is pursuing the technological transfer and local adaptation of these solutions, so that they are compatible with the national climatic, pedological and economic particularities.

RESULTS

The inclusion of these equipment in the testing and validation systems at the experimental level ensures the convergence of Romanian research with international trends in the field of precision agriculture and green mechanization. Thus, Romania not only follows, but also actively contributes to the global development of technologies for sustainable agriculture, providing models of good practices for the countries of Central and Eastern Europe.

The technologies developed fit perfectly into the directions promoted by this strategy. They contribute to achieving European objectives by: optimizing resource consumption, through precision work and reducing losses; decreasing soil and air pollution, by making fuel consumption more efficient and reducing soil compaction; increasing economic and social efficiency, by reducing production costs and improving working conditions in the orchard. The experimental data were recorded in observation sheets and statistically processed using classical methods of variance analysis, with the determination of the significance of the differences. For the interpretation of the economic data, cost-benefit analysis and simple depreciation were used. The comparison of results with international data was carried out by referring to publications from Italy, France and Germany, where similar equipment such as *root-pruner*, *mechanical blossom thinner* or *orchard work platform* have been implemented on a commercial scale (*Khurshid et al.*, 2023; *Chu et al.*, 2025). For each piece of equipment, detailed technical sheets were developed regarding the constructive composition, the operating principle and the way of integration into the fruit growing work flow. The tests were carried out in compliance with occupational health and safety regulations, according to Romanian legislation and EU standards regarding the safety of agricultural equipment. The photographs, diagrams and quantitative data collected were subsequently used for comparative analysis and the development of technological recommendations.

The data obtained from testing the three equipments allowed for a comprehensive evaluation of the efficiency and sustainability of the proposed technologies. The experimental results presented in the following chapter highlight both the technical performances and the economic, social and ecological impact of each innovation, compared to conventional practices used in Romanian fruit growing.

ETR

ERI

PP

Fig. 8 - Experimental models of innovative technology for maintaining fruit plantations

The root cutting equipment (Fig. 6, **ETR**) was designed and manufactured at INMA Bucharest, with the aim of regulating excessive vegetative growth of trees and optimizing the ratio between growth and fruiting. The constructive concept of the equipment is based on an active knife system, arranged laterally, which performs a controlled sectioning of the superficial roots, at a depth of about 25...35 cm, in the median area between the rows. The tests were carried out in March–April this year, in experimental apple and plum plantations, on cambic chernozem soil. The experiment compared two technological variants: v1 (control) – without root cutting and v2 (ETR) – mechanized root cutting on both sides of the row, at about 0.6 m from the tree axis.

The results obtained show a visible reduction in vegetative vigor and an improvement in fruit uniformity in trees treated with ETR. The average length of one-year-old shoots decreased by about 22%, and the average fruit weight increased by about 12.8% compared to the control. Also, fruit ripening was more uniform, and the incidence of premature fall was reduced by about 8%. From an operational point of view, the ETR equipment demonstrated good reliability, with an optimal working speed of about 2.0 km/h and an average fuel consumption. The works were carried out with an approximate productivity and a saving of about 60...65% of working time compared to manual methods of soil maintenance in the root zone.

The observed agronomic effects are consistent with international studies (*Chu et al.*, 2025), which show that controlled root pruning stimulates fruiting and stabilizes production, contributing to reducing the need for fertilizers and irrigation. The economic analysis indicates a return on investment in the next 4–5 years, depending on the farm area and fuel price. Ecologically, the ETR intervention is part of the concept of conservative agriculture, as it minimizes deep soil work and maintains good porosity in the root zone, without affecting soil biodiversity. In addition, the reduction of energy consumption and the total number of passes contributes to the decrease of greenhouse gas emissions, thus aligning the fruit growing practice with the sustainability objectives promoted at European level.

The inflorescence thinning equipment (Fig. 6, **ERI**), developed within INMA Bucharest, was designed with the aim of optimizing the fruit load regulation process in apple and plum orchards, replacing or complementing manual thinning work, characterized by high time and labor consumption. The operating principle of the equipment is based on the mechanical action of flexible active organs (rotating elastic filaments), which, at a controlled speed, removes part of the excess inflorescences, without causing damage to the vegetative buds or young shoots. The experimental tests were carried out in intensive apple orchards, during April–May this year, on the Idared and Golden varieties. Two technological variants were compared: v1 (control) – classic manual thinning, performed by specialized operators, and v2 (ERI) – mechanized thinning with experimental equipment. The results showed that the use of the ERI equipment led to a substantial reduction in working time, of approximately 70% compared to the manual version, which implies a significant saving in labor. Thus, works that previously required a team of 8 to 10 workers/ha could be carried out with only 3 operators, thanks to the high working capacity of the equipment.

Biologically, the degree of thinning achieved was between 35–40%, similar to that achieved manually, but with a higher uniformity of fruiting, the coefficient of variation decreasing by almost 30%. This uniformity was directly reflected in the increase in the average weight of the fruit by about 15% and in the improvement of commercial quality, by reducing the proportion of undersized fruit. Also, the comparative analysis of the number of fruits per tree highlighted a controlled reduction in the fruit load, without a negative impact on the total production, which increased slightly due to the superior quality of the fruits and the efficiency of the photosynthesis process. Economically, the application of the ERI thinning work led to a decrease in the total cost of the operation by approximately 60%, compared to the manual method, mainly due to the reduction in time and the number of workers involved. The energy consumption of the equipment remained low, confirming the viability of this technology also from an ecological perspective.

The sustainability analysis demonstrated that ERI contributes to reducing the carbon footprint by reducing the number of orchard passes and by streamlining resource consumption, aspects that directly align with the objectives of the European "Farm to Fork" Strategy and the European Green Deal regarding the sustainable mechanization of agriculture. Compared to the results obtained in similar research in Italy, France and the USA (*Khurshid et al*., 2023), the Romanian ERI equipment is part of the same technological trends, demonstrating that Romania can produce and test high-performance mechanized solutions for crop load regulation works.

The results obtained for ETR and ERI reinforce the idea that intelligent mechanization of tree maintenance work is essential for achieving sustainable development objectives in fruit growing. Next, the

fruit growing platform (PP) is presented, which completes the set of technologies developed at INMA for the integrated modernization of orchard work.

The fruit platform (Fig. 6, **PP**) is an innovation aimed at modernizing manual work in intensive and super intensive orchards, by automating and mechanizing maintenance, pruning, harvesting and phytosanitary inspection operations. The equipment was developed within INMA Bucharest, with the aim of improving work ergonomics, reducing operational costs and increasing worker safety in fruit farms. The prototype of the platform is designed as a modular, self-propelled structure, equipped with a hydraulic lifting system, protective railings and extendable platforms, which allow easy access to the tree crown up to heights of 3.5...4 m. During the tests carried out during January-July-October this year, the platform was used for green pruning, tying, harvesting and phytosanitary inspection in apple and plum orchards in the southern part of the country.

The results showed a considerable increase in labor productivity. In the case of harvesting operations, the average working time was reduced by about 45...50% compared to the classic method (ladders and walking on the ground), and the number of minor accidents (slips, imbalance) was reduced by over 60%, according to observation sheets and questionnaires completed by operators. The physical effort perceived by workers, rated on a scale from 1 to 5, decreased on average from 4.2 to 2.1, confirming the improvement in ergonomics and working conditions.

CONCLUSIONS

The innovative technologies for fruit growing presented contribute to the modernization of production systems, reducing the ecological impact and operating costs.

❖ *Technical and economic performance*

Technically, all the equipment contributed to a substantial reduction in working time, on average by about 50...75% compared to traditional methods. The ERI equipment shortened the duration of inflorescence thinning work by over 70%, the ETR reduced the time for soil maintenance and vegetative vigor regulation by approximately 60%, and the PP made harvesting and maintenance work more efficient by about 45...50%. From an economic point of view, the application of these technologies has led to a reduction in total production costs between 35% and 60%, due to labor savings and increased productivity. The average estimated duration of investment amortization varies between 3 and 5 years, depending on the type of equipment and the area exploited. These results are within the limits recommended by international standards for modern fruit growing technologies.

❖ *Agronomic and qualitative impact*

From a biological and agronomic point of view, the equipment analyzed had obvious positive effects:

- ERI improved fruiting uniformity and fruit quality, increasing average weight by up to 15%;
- ETR contributed to regulating vegetative growth and balancing the growth-fruiting ratio, favoring constant and uniform fruiting;
- PP ensured an ergonomic, safe and efficient performance of maintenance work, reducing the physical effort of operators by over 50%.

Through the integrated application of the three technologies, the flow of annual work in the orchard becomes more coherent, more uniform and less dependent on external factors, which directly contributes to the stability and sustainability of production.

❖ *Social and environmental benefits*

- The results obtained highlight not only economic benefits, but also major social and ecological impacts.
- Reducing fuel consumption, the number of passes in the plantation/orchard and the risks of accidents, as well as improving working conditions and operator comfort, support the transition towards environmentally and worker-friendly fruit growing.
- CO_2 emissions and preserving soil structure (especially through the use of ETR) are part of the objectives of the European Green Deal and the Farm to Fork Strategy, which promotes the sustainability and digitalization of European agriculture.

ACKNOWLEDGMENT

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THE INFLUENCE OF MAGNETISM ON THE GROWTH OF VEGETABLE PLANTS
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INFLUENTA MAGNETISMULUI ASUPRA CRESTERII PLANTELOR LEGUMICOLE

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ABSTRACT

In the context of climate change and global soil degradation, researchers have developed new ways to improve seed germination capacity, plant growth and achieve higher quality production. Among these modern methods, magneto-priming (treatment of seeds with magnetic field) has become the most popular in recent years, due to the fact that it does not pollute and is effective, improving seed vigor and plant growth. This paper describes the "magneto-priming" method, but also its spread globally and nationally, and the results of various studies in this field are briefly presented

ABSTRACT

În contextul schimbărilor climatice și al degradării globale a solului, cercetătorii au dezvoltat noi modalitati pentru a îmbunătăți capacitatea germinării semințelor, creșterea plantelor și pentru a obține o producție de calitate superioară. Dintre aceste metode moderne, magneto-priming (tratarea semințelor cu câmp magnetic) a devenit cea mai populară în ultimii ani, datorită faptului că nu poluează și este eficientă, îmbunătățind vigoarea semințelor și creșterea plantelor. În această lucrare este descrisă metoda "magneto-priming", dar și răspândirea sa la nivel global și național, iar rezultatele unor diverse studii din acest domeniu sunt prezentate pe scurt

INTRODUCTION

Magnetic priming is a technique of biostimulation of seeds by exposing them, for a controlled period of time, to a static or oscillating magnetic field. The goal is to improve the physiological processes involved in germination and the early development of seedlings.

Origin and evolution of the method

The method began to be studied experimentally in the 1980s and 1990s, particularly in Russia, India, and Middle Eastern countries, where researchers observed that exposing seeds to moderate magnetic fields can accelerate ion exchange and enzyme activity. After 2000, the technique quickly expanded in the scientific literature, with the advent of research on non-chemical biostimulants and eco-friendly crop stimulation.

Plants in which it has been used

In the last 30–40 years, magneto-priming has been successfully tested on numerous species, as we can observe in figure 1, the most common being:

- **Cereals**: wheat, corn, rice, barley
- **Legumes**: soybeans, beans, peas, lentils
- **Oilseeds**: sunflower, rapeseed
- **Horticultural**: tomatoes, peppers, eggplant, lettuce, spinach
- **Forest species and medicinal plants**
- **Model plant** (e.g.: *Arabidopsis thaliana*)

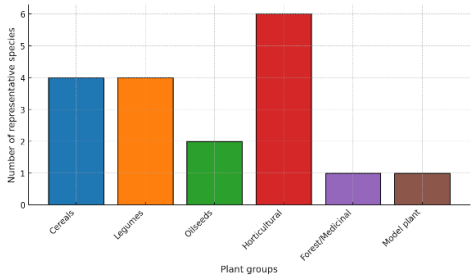

Fig. 1 – Plant groups successfully tested with magneto priming

Global spread

Currently, magneto-priming is studied and experimentally applied in:

- **Asia** – India, China, Pakistan, and Iran are major research centers.
- **Europe** – Spain, Portugal, Italy, Poland, Hungary have numerous recent studies.
- **South America** – Brazil and Argentina began publishing intensively after 2015 (including the study *by Faria et al., 2023*).
- **North Africa** – Algeria, Egypt and Morocco use the technique in studies of drought-resistant crops.
- **North America** – research is on the rise, although practical application on farms is still limited.

The global spread is largely academic, but practical interest is growing due to the fact that the method requires no chemicals, has low costs, and can be integrated into seed treatment programs for sustainability.

National spread

The studies analyzed for this paper suggest that there is Romanian research on the topic of stimulation of seeds/plants with electromagnetic fields. Currently, most of the results in this field come from the university / research environment (USAMV Iași, Cluj, NARDI Fundulea), not from the reports of large farms that widely apply magneto-priming. This suggests that the method is more in the research phase than in the commercial adoption phase at a wide level in Romania.

In Romania, one of the clearest demonstrations of the use of magnetic fields in seed treatment comes from USAMV Iași, where researchers applied ELF magnetic fields (0 and 50 Hz) to tomato seeds and observed significant effects on the germination rate and vigor of seedlings *(Cazacu et al., 2020).*

At USAMV Cluj-Napoca, researchers investigated the effect of electromagnetic fields on Phaseolus vulgaris plants grown in protected areas, the results indicating physiological changes and possible productivity increases *(Păcurar et al., 2014).*

At the national level, related methods — such as the use of magnetic nanoparticles — have been studied at NARDI Fundulea, where applications on wheat have shown anatomical changes and improved nutrient absorption potential *(Grigore et al., 2021).*

At USAMV Bucharest there are experimental studies on okra seeds treated with variable magnetic field before sowing, demonstrating the growing interest of the Romanian academic environment in this technique *(Stoica et al., 2023).*

In our country, magnetic priming is of interest to researchers, so not only seeds are being studied, but magnetic nanoparticles for fertilization are also being explored, which indicates a broader interest in magnetic technologies in Romanian agriculture, not just priming. Studies such as the above indicate that there are experimental projects and potential to extend the method to horticultural plants and perhaps in the future to large crops if the results prove significant. In figure 2 we can observe magnetic treatment on soybean seeds.

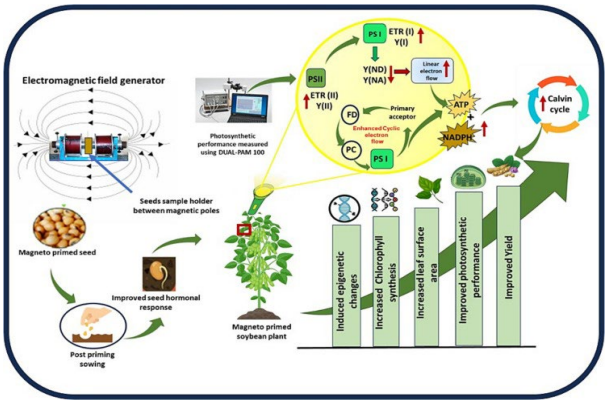

Fig. 2 - Magnetic treatment on soybean seeds (https://www.sciencedirect.com/science/article/abs/pii/S1011134425000697)

MATERIALS AND METHODS

Soybean (*Glycine max*) is one of the most important proteins and oilseed crops in the world due to a boom in its demand. In order to meet this demand, various modern agricultural methods are being employed, to improve seed vigour, growth and yield of soybean plants. Magneto-priming (treatment of seeds with magnetic field) is a popular technique owing to its efficiency and eco-friendly nature. De Faria et al., present in the study "The effect of magneto-priming on the physiological quality of soybean seeds", conducted in

2023, a detailed *magneto-priming* experiment applied to soybean seeds; the authors used static/oscillating fields and measured physiological quality parameters: % germination, germination times, vigor, stress-related enzymatic activities (catalase, peroxidase), and the expression of some genes associated with stress response. Possible mechanisms are analyzed: increased membrane permeability, activation of antioxidant systems and modulations in the expression of stress response genes. Figure 3 shows the growth effects of soybean sprouts, and the significant difference between the control sample and the sample treated by magneto-priming can be observed. Table 1 briefly present the results obtained by magneto-priming on soybeans *(de Faria et al., 2023)*.

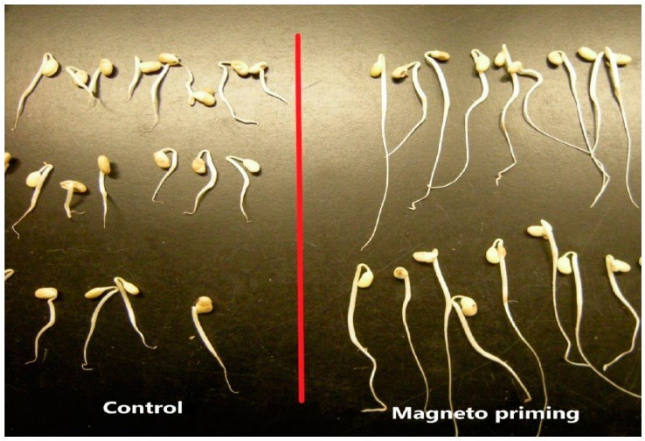

Fig. 3 - The effect of magnetic treatment on soybean seeds
(https://www.researchgate.net/publication/369604671_The_Effect_of_Magneto-Priming_on_the_Physiological_Quality_of_Soybean_Seeds/figures**)**

In the study "Magnetopriming enhance germination and seedling growth parameters of onion and lettuce seeds" *(Sari, M. E. et al., 2023)*, onion seeds (Allium cepa L.) and lettuce (Lactuca sativa L.) were used as biological material. The seeds were pre-hydrated in distilled water before exposure to a static magnetic field (MF) of predefined intensity and duration (e.g. 60 mT × 30 min for onions, or 30 mT × 60 min for low-quality batches). The magnetopriming treatment was followed by sowing under standardized germination conditions (constant temperature, controlled light). The parameters measured included germination percentage (GP), seedling emergence percentage (SEP), mean germination time (MGT), root and hypocotyl length, fresh and dry mass of seedlings and seedling uniformity. Statistical analyses were performed for the comparison between the treated group and the control, with meanings considered at $p < 0.05$. In figure 4 we can see the various morphological, physiological and biochemical effects of the magnetic field on plants. In Table 2 the results of this study are summarized.

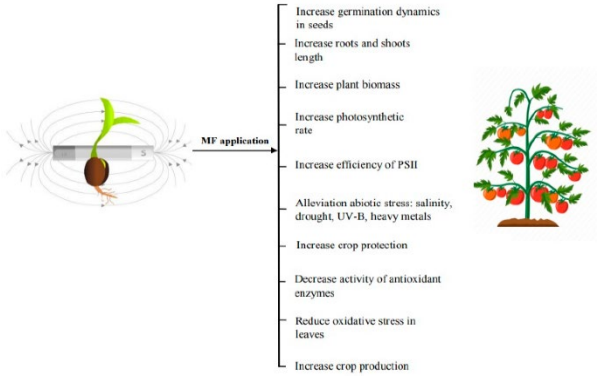

Fig. 4 - The multiple effects of the magnetic field on plants (https://www.mdpi.com/2223-7747/9/9/1139# https://www.mdpi.com/2223-7747/9/9/1139#)

In the study called "Seed priming methods tested on Salvia officinalis L.", *Stoian et al., (2024)* make a comparison between priming methods (hydropriming, osmopriming, electro-priming and magneto-priming) on sage seeds. The authors evaluate germination, germination times, vigor and initial phenotypic parameters.

The experiments were carried out under laboratory conditions, in a germination chamber with continuous light, constant temperature of 20 ± 2 °C and relative humidity of about 40% *(Stoian et al., 2024).*

Salvia officinalis (sage) seeds from a local population in Romania were sterilized (hypochlorite solution → distilled water) before priming *(Stoian et al., 2024)*. Four treatments were compared: (1) control (without priming), (2) hydro-priming (in distilled water for 48 h), (3) electro-priming (exposing the seeds for 20 minutes to an electric field between two plates, 25 V, distance 15.8 cm) and (4) magneto-priming (exposing the seeds for 20 minutes in a Helmholtz coil generating a uniform magnetic field of 0.22×10^{-3} T) *(Stoian et al., 2024).* Following the treatments, the seeds were germinated (100 seeds × 4 repeats for each treatment) and monitored daily for 14 days, using the coding of the germination stages according to the standardized BBCH scale (sub-stages 05-09) for each replicate *(Stoian et al., 2024).* Germination indices (GI), mean germination time, coefficient of variation of germination time (CVt) and the interval of days for each BBCH sub-stage were recorded *(Stoian et al., 2024).* Photographing seedlings in secondary stages was performed with a stereoscopic microscope to follow the transitions between sub-stages and highlight differences in speed and uniformity between treatments *(Stoian et al., 2024).*

Based on germination speed, combined with the day of the half and final germination percentage, the treatments showed multiple differences (Table 1). The results indicate significant differences ($p < 0.05$) between the four treatments applied to *Salvia officinalis L seeds.*, reflecting the distinct mode of action of each type of priming on the germination process:

1. *Hydro-priming (H)* recorded the highest values for the main germination stages, with 66.7 % germinated seeds on day 5 (D5D5), 71.33 % on day 6 (D6D6) and 71.6 % on day 8 (D8D8), compared to control (36–62 %). It also achieved the highest Germination Index (GI = 25.06 ± 0.47) and Germination Value (Gval = 97.37 ± 1.03), indicating both speed and high germination intensity. The increased values of these indicators confirm that controlled hydration effectively stimulates the metabolism of seeds before complete imbibition.
2. *Magneto-priming (M)* exhibited a distinct behavior: although the percentage of germination at the beginning the test (D5D5 = 33.33 ± 13.1 %) was inferior to hydro-priming, the treatment generated the most uniform germination, reflected by the lowest coefficient of variation (CVt = 24.66 ± 1.75) and a stable mean germination time (MGT = 0.31 ± 0.02). Despite the lower values of GI (14.63 ± 1.35) and Gval (46.95 ± 0.70), the uniform distribution of germination suggests a physiological stabilization effect of seedlings, an essential phenomenon in the production of homogeneous and adaptable seedlings.
3. *Electro-priming (E)* produced an intermediate germination, with values close to the control at D5D5 (54.66 ± 7.26), but superior to other parameters, such as GI (17.92 ± 2.30) and Gval (71.98 ± 1.87), suggesting that electrical stimulation may improve germination, but with increased variability (CVt = 47.30 ± 7.43). Control (C) showed the lowest performance, confirming the need for biostimulation to optimise germination in this medicinal species.

In conclusion, hydro-priming maximizes the germination performance, being the most efficient method for quickly and intensively increasing the germination percentage of sage, while magneto-priming stands out for the uniformity of the seedlings obtained, which can be decisive in horticultural systems that prioritize the visual quality and homogeneity of seedlings. While hydro/osmopriming can provide improvements to other parameters (water reserve, tolerance to osmotic stress), they are concluding that magneto-priming offers specific advantages for certain parameters (e.g. shorter germination times).

Table 1

Differences in germination parameters induced by treatments *(Stoian et al., 2024)*

P/Treat	C	E	H	M
D5D5	36±8.32ab	54.66±7.26ab	66±7.57a	33.33±13.1b
D6D6	54.66±3.52ab	56±7.23ab	71.33±5.20a	41.33±12.8b
D8D8	62.66±3.52a	57.66±6.38a	71.66±4.91a	58±1.52a
D10D10	65.33±2.66a	64.33±8.68a	72±4.61a	58±1.52a
GIGI	16.52±1.30b	17.92±2.30ab	25.06±3.47a	14.63±1.35b
PeakPeak	11.64±1.09b	13.66±1.81ab	17.44±1.28a	10.52±1.30b
GvalGval	58.17±3.99b	71.98±17.0ab	97.37±13.0a	46.95±6.07b
MGTMGT	0.23±0.03b	0.29±0.01b	0.31±0.02a	0.23±0.03b
CVtCVt	32.55±4.09ab	47.30±7.43a	31.91±3.40b	24.66±1.75b

*Note: Mean ± S.E. followed by different letters presented significant differences at p<0.05 (LSD test) among the treatments within each table line. Legend: D – Assessment days, C – Control, E – Electro-priming, H – Hydropriming, M – Magneto priming. GI – germination index, Peak – germination peak, Gval – germination value, MGT – mean germination time, CVt – coefficient of variation of the germination time.

RESULTS

In the first study, "The effect of magneto-priming on the physiological quality of soybean seeds", the results show significant improvements in germination speed and percentage at certain combinations of intensity and duration compared to the control, as well as a decrease in lipoid peroxidation markers. At the same time, it signals the variability of the response depending on the seed batch and the need for large-scale and field validation. We can see in Table 2 the synthesized results that highlight the positive impact of magneto-priming on the physiological performance of soybean seeds, especially for the analyzed cultivars:

- The magnetic field treatment has increased the percentage of germination, with a more pronounced in the case of cultivar C02, which confirms the differentiated sensitivity of genotypes to electromagnetic biostimulation.
- The effects on germination vigor are evidenced by increasing the number of normal seedlings to the first count, which suggests an acceleration of the initial processes of embryonic development. In parallel, the decrease in the percentage of abnormal seedlings indicates a beneficial effect of the treatment on the morphological integrity of the seedlings, possibly in relation to the modulation of oxidative stress and cell repair.
- At the morpho-physiological level, magneto-priming significantly stimulated root growth (and sometimes hypocotyl) in cultivar C02, an important indicator for the competitiveness of seedlings in the early stages of vegetation. At the same time, fresh and dry biomass increased especially for the hypocotyl of cultivar C01, indicating variable effects between organs and genotypes.
- Acceleration of water absorption in treated seeds has been found , reflecting a process of metabolic activated more efficiently from the imbibition phase, with direct implications on the initiation of germination.
- Magneto-priming influenced seed longevity, increasing P50 by approx. +0.88 days (C01) and +0.95 days (C02), which demonstrates that the treatment contributes to maintaining medium-term viability under stressful storage conditions. These results were also confirmed by Box–Cox survival models, where the treated seeds showed a superior performance to the controls.
- At the molecular level, increased expression of the HSFA3, HSP21, HSP17.6b, EXP and ABI3 genes suggests that magneto-priming activates signaling pathways involved in stress tolerance, protein protection, and cell expansion, thus explaining the coherence between physiological effects and genetic response.

Overall, magneto-priming improves the germination, vigor, uniformity and longevity of soybean seeds, with cultivation-dependent variations, supporting its applicability as a sustainable method of biostimulation.

Table 2

Results obtained by magneto-priming on soybeans *(de Faria et al., 2023)*

Evaluated Parameter	Effect Observed After Magneto-Priming (compared to Control)
Total germination	Increased in both cultivars, more pronounced in C02
Seedling vigor (first count)	Higher number of normal seedlings in C02
Abnormal seedlings	Reduction in the percentage of abnormal seedlings under some parameters
Root / hypocotyl length	C02 showed significantly longer root (and sometimes hypocotyl)
Fresh / dry mass	Increased biomass (especially C02, and hypocotyl in C01)
Water uptake	Faster and higher water absorption curve in treated seeds
Longevity (P_{50})	+0.88 days (C01), +0.95 days (C02) indicating extended seed viability
Long-term survival	Box–Cox survival model showed better performance in treated seeds
Gene expression	Higher expression of HSFA3, HSP21, HSP17.6b, EXP, and ABI3 after treatment

Regarding the study “Magnetopriming enhance germination and seedling growth parameters of onion and lettuce seeds” *(Sari, M. E. et al., 2023)*, the results obtained by magneto-priming on onion and lettuce are presented in Table 3.

- The results obtained for onion seeds (*Allium cepa L.*) and lettuce (*Lactuca sativa L.*) highlights the stimulating effects of magneto-priming on the germination and emergence process. In the case of both species, the germination percentage increased significantly compared to the control, reaching up to 80% in onions and about 87% in salads. This effect indicates that pre-sowing exposure to static magnetic field optimizes the initial phases of imbibition and activation of latent seed metabolism.
- In terms of the percentage of seedling emergence (SEP), the magnetic treatment led to **increases** of up to 76% in onions and ~86% in lettuce, the values suggesting an efficient transition of seedlings from the germination stage to full emergence. This demonstrates that, in addition to stimulating initial biochemical processes, magneto-priming supports the stability of subsequent seedling development.
- Shortening the average germination time (MGT). The untreated seeds showed an MGT of about 1.9 days, while those subjected to magneto-priming reached emergence in about 1.1 days, especially in the case of lettuce. The reduction of MGT indicates a faster initiation of the enzymatic and physiological processes necessary for root elongation, which provides a competitive advantage in the early stages of growth.

Overall, magneto-priming applied to onion and lettuce seeds increases germination efficiency, improves the emergence rate and reduces the time needed for seedlings to appear, these being solid arguments for integrating the method into horticultural technologies that aim to increase crop uniformity and reduce seedling production time.

Table 3

Results obtained by magneto-priming on onion and lettuce *(Sari, M.E. et al., 2023)*

Parameter	Observed Effect after Magnetopriming vs Control
Germination percentage (GP) – onion	Up to ~80% vs lower in control
Germination percentage (GP) – lettuce	Up to ~87% in treated seeds
Seedling emergence percentage (SEP) – onion	Up to ~76% treatment
Seedling emergence percentage (SEP) – lettuce	Up to ~86% treatment
Mean germination time (MGT)	Shorter MGT in treated seeds (ex: from ~1.9 days untreated to ~1.1 days treated in lettuce)

In the study called "Seed priming methods tested on Salvia officinalis L.", *Stoian et al., (2024),* researchers concluding that magneto-priming offers advantages like shortly germination time, while other methods, like hydro/osmopriming can provide improvements to other parameters, like water reserve and tolerance to osmotic stress. Table 4 summarises the performance obtained by applying different priming methods to *Salvia officinalis L seeds.*, highlighting significant differences between treatments.

- Hydro-priming generated the best results overall, resulting in a final germination percentage of 70–71%, as well as the fastest transition to >50% germination, in about 5 days. At the same time, this treatment led to the highest value of the germination index (GI = 25.06 ± 3.47), which emphasizes both the intensity and the speed at which germination occurs.
- The electro-priming showed intermediate values, with slightly superior performance to the control (64% compared to 65% final germination in the case of control), but without consistent advantages in terms of speed or uniformity. This suggests that electrical stimulation may induce positive effects, but less effective than controlled hydration.
- In contrast, magneto-priming produced a distinct effect: although the final germination percentage is modest (over 50%), the treatment induced the most uniform germination, as demonstrated by the lowest value of the coefficient of variation (CVt = 24.66 ± 1.75). This characteristic highlights an important advantage for the production of quality seedlings, especially in commercial horticulture where the homogeneity of the batch is an essential criterion.
- At the same time, magneto-priming maintained a stable average germination time (MGT = 0.23 ± 0.03), similar to the control, signaling a constant development, but slower than in the case of hydro-priming.

Therefore, the results indicate that hydro-priming is the optimal method for maximizing and accelerating the germination of sage seeds, while magneto-priming is superior in the uniformity of seedlings, becoming a valuable alternative when the main objective is to obtain homogeneous and standardized seedlings from a morpho-physiological point of view.

Table 4

Comparation between priming methods on Salvia officinalis (Stoian et al., 2023)

Treatment	Final germination %	Days to >50% germination	Germination Index (GI)	Mean Germination Time (MGT)	Coefficient of Variation (CVt)
Control	~65 %	~6 days	~16.52 ± 1.30	~0.23 ± 0.03	~32.55 ± 4.09
Electro-priming	~64 %	~6 days	~17.92 ± 2.30	~0.29 ± 0.01	~47.30 ± 7.43
Hydro-priming	~70–71 %	~5 days	~25.06 ± 3.47	~0.31 ± 0.02	~31.91 ± 3.40
Magneto-priming	>50 %	~8 days	~14.63 ± 1.35	~0.23 ± 0.03	~24.66 ± 1.75

Although magneto-priming affects all species positively, its specific advantages differ among studies, enhancing vigor and longevity in soybean, accelerating germination in onion and lettuce, and providing superior uniformity in sage. In figure 5 are showed a comparative ranking of magneto priming across mentioned studies.

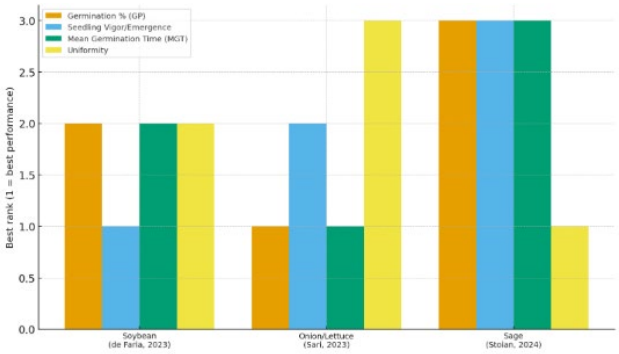

Fig. 5 - Comparative ranking of magneto priming across studies

CONCLUSIONS

A. The study by de Faria et al. (2023) shows that magneto-priming applied to soybeans:

➢ Improves the physiological quality of seeds: increases germinability, vigor and reduction the proportion of abnormal seedlings.

➢ It stimulates the development of seedlings: especially in certain cultivations, longer roots and a higher biomass of seedlings.

➢ Optimizes water absorption dynamics: treated seeds show more effective hydration and more favorable dynamics of the imbibition process.

➢ Increases seed longevity (P_{50} higher) under storage stress conditions, indicating that Magneto-priming can also be used as a method of maintaining quality in the medium term.

➢ It alters the expression of key genes related to stress and germination, supporting the idea that the effects are not not only morpho-physiological, but also molecular.

In conclusion, for soybeans, magneto-priming appears as an effective tool for integrated improvement of physiological quality and seed lifespan.

B. In the case of the study by Sari et al. (2023), magneto-priming applied to onion and lettuce seeds:

- It increases the germination percentage and improves the vigor parameters, both by uniforming seedlings, as well as by increasing the length of the roots and the hypocotyl.
- It reduces the average germination time, especially in salads, which makes it easier to obtain faster and more homogeneous seedlings.
- Produces seedlings with higher biomass, suggesting that the treatment positively influences

processes physiological aspects of the early stages of development.

Overall, the study confirms that for horticultural species of economic importance, magnetopriming can be integrated as a practical method of seed preparation, with direct effects on seedling quality.

C.The study by Stoian et al. (2024), comparing hydro-priming, electro-priming, and magneto-priming to Salvia officinalis:

❖ It shows that all types of priming can improve germination over the control, but hydro-priming it offers, in this case, the best results in terms of final germination percentage and germination index.

❖ Magneto-priming, however, produces improvements over the indicator for certain parameters, but it is more poorly performed than hydro-priming in terms of final germination percentage and overall speed of transition between BBCH stages.

The study emphasizes that the effectiveness of magneto-priming depends on the species and that, in salvia officinalis, it can be useful especially as a complementary tool or in combination with other methods, especially when aiming to optimize specific parameters (e.g. certain BBCH stages, uniformity in certain phases).

The analyzed studies highlight the fact that magnetic field-based seed priming treatments can represent a sustainable biostimulation alternative, with beneficial physiological effects on different agricultural and horticultural species. Magneto-priming applied to soybean seeds contributes to more vigorous and stable seedlings, with superior behavior in water absorption, a reduced incidence of abnormal seedlings and greater seed longevity, supported by molecular changes in the expression of genes responsible for stress tolerance. In fast-germinating horticultural species, such as lettuce and onions, the effects of treatment are individualized by increasing the germination rate and shortening the seedling emergence time, which can reduce the duration of the production phase of the planting material. In Salvia officinalis, magneto-priming does not maximize germination, but it is distinguished by the uniformity of the seedlings, an aspect of practical interest in obtaining homogeneous seedlings, suitable for standardized cultivation. The results suggest that the effects of the magnetic field are species-dependent and metabolic dynamics, which implies the need to optimize treatment parameters for different crops, but confirm the potential of this method in increasing seed quality and performance without additional chemical input.

General conclusions:

Magneto-priming, as a whole, is a physical, non-chemical method that when applied correctly, improves germination, seedling vigor and sometimes seed longevity, but the effects strongly depend on the species, field parameters and initial seed quality. Magneto-priming of seeds is a biostimulation strategy that combines technological simplicity with a high potential for application in agriculture and horticulture. In general, the results in the literature indicate:

❖ Increasing the germination percentage and shortening the germination time, especially in species with slow or stress-sensitive germination.

❖ Improving seedling vigor (root and hypocotyl length, fresh biomass and dry), which can translate into more competitive seedlings in the early stages of vegetation.

❖ Modulation of water absorption and activation of initial metabolism (faster hydration, activation enzymatic stress), with possible implications for resistance to abiotic stress.

❖ Possible effects on gene expression and stress response mechanisms, suggesting that Magneto-priming is not just a passive physical effect, but interacts with cellular signaling systems.

At the same time, studies also highlight the fact that:

➢ The effects are species-specific and even cultivar-specific.

➢ The intensity/duration window seems to be optimizable – doses that are too low or too high may have weak or even neutral effects.

➢ Methodological standardisation is still limited, which makes it difficult to directly compare studies.

Overall, the available data suggest that magneto-priming is an effective method of seed biostimulation, with positive effects on germination, seedling vigor and, in some cases, seed longevity. The results obtained in soybeans *(by Faria et al., 2023)* and horticultural species such as onions and lettuce *(Sari et al., 2023)* highlight significant increases in germination percentage, shortening emergence time and improvement of growth parameters in early stages. At the same time, the comparative study carried

out on *Salvia officinalis (Stoian et al., 2024)* shows that the efficiency of magneto-priming is strongly dependent on the species and may be inferior to other methods, such as hydro-priming, for certain crops.

These results support the idea that magneto-priming has a real potential for use in agriculture and horticulture, but optimizing treatment parameters and adapting them to each species remains essential to achieve reproducible and agronomic relevant effects.

In conclusion, magneto-priming is not always the "best" treatment of all forms of priming, but it remains a viable option and relatively simple to apply, with positive effects, but varying depending on the species and methodology.

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STUDY ON MAGNETISM, ITS ADVANTAGES AND DISADVANTAGES IN DIFFERENT CROPS / *STUDIU PRIVIND MAGNETISMUL, AVANTAJELE SI DEZAVANTAJELE ACESTUIA LA DIFERITE CULTURI*

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Keywords: *static or pulsating magnetic fields, seeds germination, fertilizers, magnetization of irrigation water*

ABSTRACT

For an innovative approach in modern agriculture, different methods have been developed. Magnetism is one of them, being non-invasive and ecological. It refers to the use of magnetic fields to influence plant growth, seed germination, and soil quality. This method includes seed treatment with static or pulsed magnetic fields, magnetization of irrigation water and application of magnetic fields on nutrients or fertilizers. This paper briefly presents this method, its advantages and disadvantages, and also possible prospects for the future.

ABSTRACT

Pentru o abordare inovatoare in agricultura moderna, au fost dezvoltate diferite metode. Magnetismul este una dintre acestea, fiind non-invaziva si ecologica. Se refera la utilizarea campurilor magnetice pentru a influenta cresterea plantelor, germinarea semintelor si calitatea solului. In cadrul acestei metode sunt incluse tratamentul semintelor, cu campuri magnetice statice sau pulsate, magnetizarea apei de irigare si aplicarea campurilor magnetice asupra nutrientilor sau fertilizantilor. In aceasta lucrare este prezentata pe scurt aceasta metoda, avantajele si dezavantajele sale, și, de asemenea, posibile perspective pentru viitor.

INTRODUCTION

Magnetism in agriculture is an innovative and environmentally friendly approach, whereby magnetic fields are used to influence plant growth, seed germination, irrigation efficiency, and soil quality *(Ibrahim et al., 2022, Hamza et al., 2025).* The most studied methods include magnetization of irrigation water, which can improve nutrient absorption and reduce the effects of salt stress *(Jamil et al., 2023; Mostafa, 2020),* treating seeds with static or pulsed magnetic fields, which accelerate germination and stimulate plant biomass *(Makhadmeh, 2021),* and applying magnetic fields to fertilizers, to increase nutrient bioavailability *(Saju et al., 2024).* Recent studies highlight positive effects on grain and vegetable yield, resistance to abiotic stress, and fruit and vegetable quality, although the molecular mechanisms are not yet fully elucidated *(Zhang et al., 2024; Hamza et al., 2025).* Overall, the use of magnetic fields in agriculture offers important potential for crop sustainability, reducing water consumption and improving productivity in a non-invasive way, helps seed enhancement and pest control, improve the soil properties, the postharvest losses are reduced, and can also help increase plants tolerance to environmental stress. In figure 1 is presented the effect of magnetic field on sustainable agricultural production.

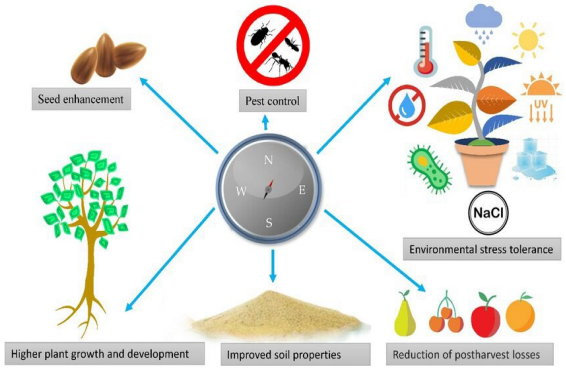

Fig. 1 - The effect of magnetic field on sustainable agricultural production (https://www.researchgate.net/figure/Effect-of-magnetic-field-on-sustainable-agricultural-production_fig1_364162159)

MATERIALS AND METHODS

In the context of modern agriculture, the application of magnetic fields is carried out with the help of methods that aim to optimize physiological processes, improve the absorption of nutrients and increase the efficiency of resource use in agricultural systems, predominantly through four technological directions:

I. Magneto-priming of seeds;
II. Seed treatment by static or pulsed magnetic fields;
III. Magnetization of irrigation water;
IV. Exposure of nutrients or fertilizers to magnetic fields.

I. *Magneto-priming (treatment of seeds before sowing)*

Magneto-priming is the exposure of seeds to controlled magnetic fields, before sowing, in order to accelerate the biochemical germination processes. In most recent protocols, seeds are exposed for 5–30 minutes to static magnetic fields with intensities between 50–200 mT, arranged in a chamber with NdFeB permanent coils or magnets, without frequency variations, followed by immediate sowing (Makhadmeh, 2021; Okumuș et al., 2023). Parameters tracked in the studies include germination percentage, germination rate, root and coleoptil growth rate, antioxidant enzyme content, and total biomass. Statistical analysis is performed by ANOVA with differentiation LSD ($p \leq 0,05$). In figure 2 – (A) we can observe the steps of magnetopriming from seed to plant maturity, while in figure 2 – (B) we see the various effects of magnetopriming from seed germination to plant maturity and that contribute to enhance photosynthetic performance under nonstress and stressed conditions.

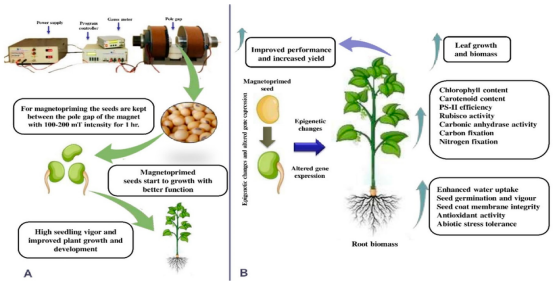

Fig. 2 - (A) Steps of magnetopriming from seed to plant maturity; (B) Various effects of magnetopriming from seed germination to plant maturity (https://www.researchgate.net/figure/A-Steps-of-magnetopriming-from-seed-to-plant-maturity-B-various-effects-of_fig1_354207817)

II. *Treatment of seeds with static or pulsed magnetic fields*

Unlike conventional magneto-priming, this method uses *static (uniform) or pulsed (flashing) fields*. Pulsed fields are generated by electric coils powered at intensities between 0.5–5 mT, with frequencies of 10–50 Hz, with exposure ranging from 2 to 20 minutes (Ibrahim et al., 2022). The methodologies include:

1. Static unidirectional exposure with gaussmeter intensity measurement

In figure 3 we can observe an electromagnetic field generator with variable magnetic field strength (50–500 mT) and a pole gap of 5 cm, used for seed treatment in static magnetic field (50–500 mT), with specimen positioned between poles (adapted from Joshi-Paneri et al., 2023).

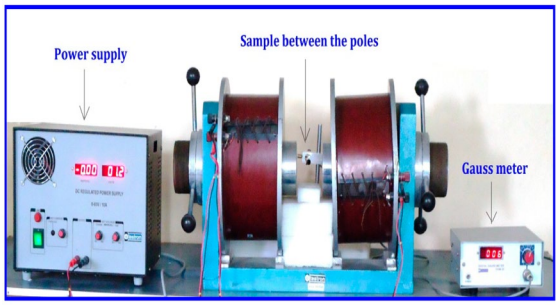

Fig. 3 - Electromagnetic field generator with variable magnetic field strength (50–500 mT) and a pole gap of 5 cm (https://pub.mdpi-res.com/seeds/seeds-02-00006/article_deploy/html/images/seeds-02-00006-g001.png)

2. Pulsed exposure with simultaneous frequency and duration control in electromagnetic generator

In figure 4 is presented a sequenced pulsed magnetic field (PMF) treatment system (a), The waveform (b) of the induced electric field (by using a search coil probe), the current (I = 5 Amp, via a resistor 0.1 ohm) and magnetic field (1 mT, with hall-effect probe) were monitored and measured during the experiments using an oscilloscope. PMF treatments were presented in repeated three sequences. Each

sequence included four different consecutive pulse trains, 1, 3, 5, and 7 Hz for PMF-1 and 7, 9, 12, and 14 Hz for PMF-2 (c)

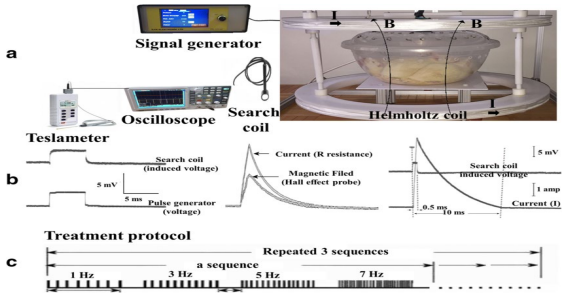

Fig. 4 - Schematic drawing of a sequenced pulsed magnetic field (PMF) treatment system (a)
(https://www.researchgate.net/figure/Schematic-drawing-of-a-sequenced-pulsed-magnetic-field-PMF-treatment-system-a-The_fig1_341891644**)**

The effects are evaluated by seed ecobiological test (germination, vigor index, root biomass), biochemical analyses (phenolic content, antioxidant enzymes) and physiological parameters in the early phase of the plants (total chlorophyll, RWC).

III. *Magnetization of irrigation water*

This technique involves passing the water through a fluid magnetization system before distribution in the irrigation plant. Contemporary studies use devices with bipolar placed NdFeB magnets, generating fields with an intensity of 0.12–0.18 T, with the water being magnetized only once before entering the main pipe (Mostafa, 2020; Jamil et al., 2023). The treatments are differentiated between:

1. *non-magnetised water (control)*
2. *magnetized water*
3. *magnetized water + fertigation before/after magnetization* (only in agricultural studies with controlled fertilization)

The monitored parameters include electrical conductivity (EC), soil salinity (ECe), foliar index (LAI), aboveground biomass, commercial production and water productivity (kg/m³). In figure 5 we see how in the experiment with Salvia virgata under salinity stress, the application of magnetized water helped plant growth, by improving water use efficiency.

Fig. 5 - The effect of magnetized water on Salvia virgata under salinity stress
https://www.sciencedirect.com/science/article/abs/pii/S0304423823001103

IV. *Application of magnetic fields to nutrients/fertilizers*

This method involves exposing nutrient solutions or liquid fertilizers to the magnetic field prior to application. In experiments in recent years, the solutions are passed through a magnetization system identical to that of water, but after the fertilizer has dissolved, in order to increase the mobility of ions and the bioavailability of macro- and microelements (Mar, 2024; Kou, 2024).

Magnetized fertigation can be:

- *with fertilizer passed through the magnetization of the water;*
- *with fertilizer added after magnetization* to assess differences in salt mobility.

The effects are analyzed by ionic concentration in soil (NO_3^-, PO_4^{3-}, K^+), absorption on plant tissues (mg/kg s.u.), crop productivity and nutrient use efficiency (NUE). In figure 6 we can observe the methodology used for the application of magnetized water together with solution treatments and the results obtained and how magnetized solution could act as an elicitor agent to mimic the stress condition, but at the lesser level resulting in activation of grape physiological and biochemical processes and elemental state through stress-related responses.

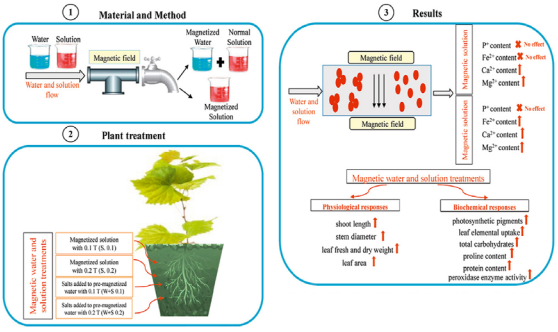

Fig. 6 - The application of magnetized water together with solution treatments and the results obtained.
https://www.sciencedirect.com/science/article/abs/pii/S0981942821004460

RESULTS

I. *Magneto-priming efficiency*

According to recent studies, magneto-priming causes a significant acceleration of germination and vigor of young plants, due to the intensification of seed metabolism. Exposure of seeds to static magnetic fields (50–200 mT) led to increased germination rate, root length, and chlorophyll content, while reducing oxidative stress by activating antioxidant enzymes (*Makhadmeh, 2021; Okumuş et al., 2023*). Overall, the treatment favoured the achievement of higher biomass in the early phase, which indicates potential to increase crop productivity. In figure 7 we can observe the semnificative difference in growth, to soyabean, between control germs and germs treated by magneto-priming:

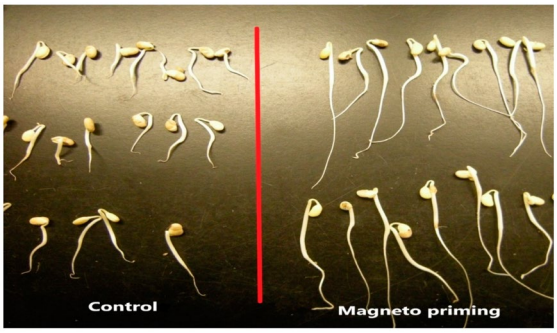

Fig. 7 - The effects of magneto-priming on soyabean germs (https://www.researchgate.net/figure/A-Steps-of-magnetopriming-from-seed-to-plant-maturity-B-various-effects-of_fig1_354207817)

II. *Effects of static or pulsed magnetic fields on seeds*

The application of static or pulsed magnetic fields has shown pronounced physiological and biochemical effects, manifested by stimulating the activity of enzymes involved in respiration and growth, increasing phenolic content, and intensifying photosynthesis (*Ibrahim et al., 2022*). Pulsed fields (10–50 Hz) produced more pronounced increases in vigor and germination index, and uniform static fields improved root development and tolerance to salt stress, indicating the complementarity of the two approaches. In figure 8 we observe the effect of pre-sowing magnetic field treatment of soybean seeds on growth at (a) early stage (35 DAE) and (b) later stage (55 DAE).

Fig. 8 - Photograph showing effect of pre-sowing magnetic field treatment of soybean seeds on growth at (a) early stage (35 DAE) and (b) later stage (55 DAE) (https://www.mdpi.com/2674-1024/2/1/6?)

III. *Impact of Irrigation Water Magnetization*

Experimental results on magnetized water irrigation have demonstrated reduced soil salinity and significant increases in crop productivity, especially in arid conditions. In pepper cultivation, magnetized water caused increases in leaf index, fruit yield, and water use efficiency (*Jamil et al., 2023*). Potato studies show that water magnetization, along with fertilizer application, led to increased tuber mass and commercial value, with superior results when fertilizer was applied after magnetization (Mostafa, 2020). In figure 9 are presented the effects of magnetized water infiltration with different treatments on soil water and salt distribution characteristics ((**A**,**B**): Changes in soil moisture with soil depth under different treatments; (**C**): The variation of soil salt content with soil depth under magnetization treatment).

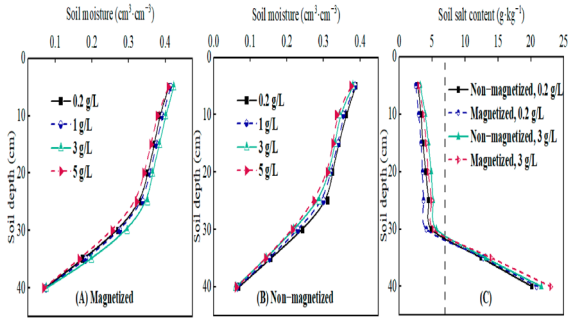

Fig. 9 – The effects of magnetized water infiltration with different treatments on soil water and salt distribution characteristics (https://www.mdpi.com/agronomy/agronomy-14-02873/article_deploy/html/images/agronomy-14-02873-g004.png)

IV. *Results of applying magnetic fields to nutrients/fertilizers*.

Exposure of fertilizers or nutrient solutions to the magnetic field has resulted in increased ion mobility and absorption of mineral elements, leading to a better valorization of nutrients at the plant level. Studies reports increased N, P and K uptake, increased nutrient value of crops and improved efficiency fertilizer use (NUE), with statistically significant increases in productivity (*Mar, 2024; Kou, 2024*).

Particularly, magnetized fertigation has generated the highest increases in both production and quality morpho-physiological aspects of plants.In figure 10 are presented the most important benefits of fertigation:

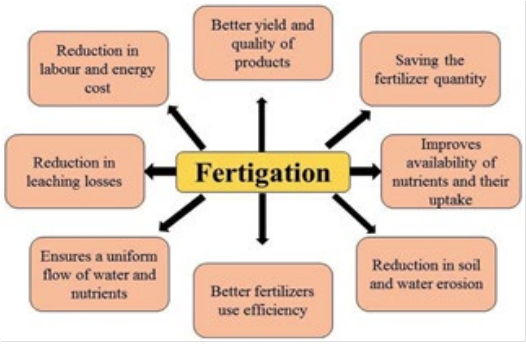

Fig. 10 – The most important benefits of fertigation (https://www.researchgate.net/figure/Advantages-of-fertigation-technique-in-agriculture_fig2_352475974)

CONCLUSIONS

The use of magnetic fields in agriculture is emerging as a sustainable and non-invasive technology, with demonstrated applicability through four major directions: *magneto-priming of seeds, treatment of seeds with static or pulsed fields, magnetization of irrigation water and exposure of nutrients or fertilizers to magnetic* fields, all of which have the effect of stimulating physiological processes, optimizing nutrient absorption and increasing resource efficiency in plant production. The main advantages and limitations specific to each method mentioned above are presented below:

I. Magneto-priming of seeds

❖ *Advantages:*

- Magneto-priming increases significantly:
- germination rate and speed;
- the vigor of seedlings;
- resistance to salt stress;

- antioxidant enzymatic activity.
- Thus, through these significant increases, it improves the physiological quality of the seeds;
- The method does not require chemical inputs and allows for fast, low-cost treatment.

❖ *Limitations:*

- Efficiency depends on:
- field intensity;
- duration of exposure;
- species.
- Lack of protocol standardization can reduce the reproducibility of results (Mar, 2024).
- Long-term efficacy remains underexplored in perennial crops.

II. *Treatment of seeds with static or pulsed magnetic fields*

❖ *Advantages:*

- The application of static or pulsed fields stimulates:
- metabolic process;
- phenolic content;
- antioxidant activity;
- photosynthesis and root development.

Thus, the result is plants with superior tolerance to stress.

Pulsed fields promote early vigor, and static ones improve salinity adaptation.

❖ *Limitations:*

- It requires strict control of the strength and frequency of the magnetic field;
- Instrumental variations can generate contradictory results.
- The effects are visible in the early stages, but the impact on final production is insufficiently quantified.

III. *Magnetization of irrigation water*

❖ *Advantages:*

- Magnetized water irrigation improves:
- water absorption;
- biomass growth;
- agricultural production;
- water use efficiency, while reducing soil salinity.

In arid crops, optimal magnetization can increase fruit quality and productivity, including in sandy agroecosystems.

❖ *Limitations:*

- Efficiency depends on:
- flow;
- duration of exposure;
- mineralogy of the water, and the effects may decrease with distance from the device.

In addition, commercial equipment costs may limit small-scale application.

IV. *Exposure of nutrients/fertilizers to the magnetic field*

❖ *Advantages:*

- The magnetization of nutrient solutions or fertilizers increases:
- ion mobility;
- absorption of macro- and microelements;
- nutrient use efficiency (NUE).
- The results showed increases in plant production and quality.
- Magnetized fertigation achieves a superior ratio between inputs and the production obtained, with direct economic benefits.

❖ Limitations:

- This method requires optimizing the timing of fertilizer application (before or after magnetization);
- Variations in the chemical composition of the solution can alter the response of plants;
- In the absence of standardization, the protocol remains difficult to apply uniformly on commercial farms.

Overall, the application of magnetic fields in agriculture is an emerging field of sustainable technologies, in a stage of accelerated scientific validation at international level and in a process of gradual expansion in applied research at national level.

The methods analyzed: *magneto-priming, seed treatment by static or pulsed fields, magnetization of irrigation water and exposure of nutrients to magnetic field* consistently demonstrate the ability to improve plant physiological performance, valorization of nutrient resources, crop productivity and water use efficiency, especially in arid or salinity-affected agroecosystems. However, the lack of a universal methodological standard, the diversity of equipment used and the variability of responses by species underline the need for continued large-scale experimental research, with a focus on reproducibility, comparative economic assessments and long-term impact on soil and horticultural products.

In the future, the integration of these techniques with smart irrigation systems, precision agriculture, biostimulants and sustainable fertilizer management can make magnetic treatments a strategic component of modern agriculture, with the potential to contribute to reducing the consumption of chemical inputs and increasing the resilience of crops to climate change. Thus, agricultural magnetism is emerging not only as an innovative technological solution, but also as an essential direction for optimizing the productivity and sustainability of the agricultural systems of the future.

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OPTIMIZATION OF AIRFLOW THROUGH THE ENCLOSURE OF AN ACTIVE COOLING SYSTEM FOR DRONE-MOUNTED ELECTRONIC EQUIPMENT

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OPTIMIZAREA FLUXULUI DE AER PRIN CARCASA UNUI SISTEM DE RĂCIRE ACTIVĂ DESTINAT ECHIPAMENTELOR ELECTRONICE MONTATE PE DRONĂ

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ABSTRACT

This paper investigates the optimization of airflow inside a protective enclosure housing critical electronic components mounted on an agricultural drone. A transient CFD model was developed in SolidWorks Flow Simulation using realistic thermal loads: pump (100 °C), HUB module (75 °C), relays (75 °C) and Li-Ion battery (65 °C). The baseline configuration shows non-uniform temperature distribution, with hot-spot formation and insufficient natural convection, resulting in maximum temperatures up to 95.6 °C. Several optimized constructive solutions were evaluated, including redesigned vent geometries, guided aerodynamic channels and the integration of a compact active fan. The optimized design significantly reduces temperature gradients and improves overall thermal stability of the electronic system, increasing operational reliability under real UAV flight conditions.

REZUMAT

Lucrarea analizează procesul de optimizare a fluxului de aer într-o carcasă destinată protecției și răcirii componentelor electronice critice montate pe o dronă agricolă. A fost elaborat un model transitoriu CFD în SolidWorks Flow Simulation, utilizând sarcini termice reale: pompă (100 °C), modul HUB (75 °C), relee (75 °C) și baterie Li-Ion (65 °C). Configurația inițială prezintă o distribuție neuniformă a temperaturilor, cu formarea de zone fierbinți și convecție naturală insuficientă, conducând la temperaturi maxime de până la 95,6 °C. Au fost evaluate mai multe soluții constructive optimizate, incluzând geometrii noi ale fantelor, canale aerodinamice interne și integrarea unui micro-ventilator. Configurația optimizată reduce semnificativ gradientele termice și îmbunătățește stabilitatea termică globală, crescând fiabilitatea sistemului electronic în condiții reale de zbor.

INTRODUCTION

Efficient heat management in electronic enclosures represents a major challenge in the context of equipment miniaturization and increasing power density. Insufficient heat dissipation frequently leads to hot spots, component degradation, and unstable performance, particularly in aerial applications where space is limited and airflow is difficult to control. Equipment integrated on drones is additionally exposed to vibrations, rapid load variations, solar radiation, and complex aerodynamic influences, which further complicate the maintenance of a safe thermal regime.

Research on passive ventilation has shown that opening geometries influence the internal microclimate of enclosures, with temperature and humidity differences being moderate but having a direct impact on measurement stability and electronic operation *(Ardiansah et al., 2021)*. This type of ventilation can be useful in static modules, but becomes limited in applications where external aerodynamic pressure is variable, such as UAV platforms.

Studies on UAV systems for medical transport have confirmed the possibility of achieving very low temperatures through active cooling and efficient control of energy consumption *(Pamula et al., 2024)*. Complementary analyses present a harmonized integration of passive and active solutions, depending on the payload type and the drone's operational conditions *(Pamula & Ramachandran, 2025)*.

High-capacity passive cooling systems, such as those based on liquid–vapor gravitational principles, have managed to dissipate heat fluxes of up to 2000 W while maintaining the interiors of electrical cabinets within safe limits, even in fully sealed configurations *(Polačiková et al., 2022).* Such approaches demonstrate the potential of phase-change heat transfer in managing high temperatures, although their adaptation to the reduced scale of UAV modules remains challenging. Dedicated analyses of heat pipes confirm their applicability in compact systems and their ability to enhance heat dissipation in isolated enclosures protected against dust and humidity *(Malcho et al., 2025).*

Thermal principles from the aerospace field provide an important technological foundation for UAV system design. Cooling of modern aeronautical equipment combines active and passive methods, using miniaturized fans, phase-change materials (PCM), heat pipes, composite materials, and advanced heat rejection strategies under extreme conditions. The need for efficient heat dissipation is intensified by the increase in local heat fluxes associated with circuit miniaturization, as highlighted in recent reviews dedicated to aeronautical and space applications *(Ersoy & Kulkarni, 2025).* In scenarios involving high thermal loads, such as drones used for fire inspection, the combination of high-temperature-resistant materials and cooling architectures adapted to hazardous environments allows stable operation of electronic components to be maintained *(Aláez et al., 2025).*

The impact of materials on thermal dissipation within a drone structure is emphasized in comparative studies on UAV frames, which have shown that aluminum significantly reduces component temperatures compared to carbon fiber due to its high thermal conductivity *(Milenin, 2025).* This finding is directly applicable to the design of electronic enclosures, where low-conductivity plastic materials tend to retain heat, while metals facilitate dissipation.

Advanced passive solutions, such as phase-change materials enriched with nanoparticles, can reduce peak component temperatures and homogenize thermal distribution during periods of intensive load. Significant cooling improvements have been achieved in configurations combining PCM with graphene, silver, or metallic foam, demonstrating the high potential of this technology for miniaturized electronic enclosures *(Hassan et al., 2022).*

Geometric optimization of enclosures constitutes another major area of interest. CFD-based studies have demonstrated that the configuration of internal airflow paths, fins, channels, and wall shapes significantly influences heat dissipation, enabling considerable reductions in internal temperatures even without increasing energy consumption *(Tarhan et al., 2025*). Experimental and numerical results on HVAC electronic units confirm that adapting radiator fin geometry or thickness can reduce component temperatures by more than 10% *(Yilmazoglu et al., 2019).* For fuel-cell-powered drones, the use of multiple fans and optimization of air inlets has proven effective in homogenizing the internal thermal environment, reducing variations by significant percentages *(Zhang et al., 2025).*

Experimental validation remains a central aspect in the development of thermal systems. CFD models of sensitive electronic devices have shown deviations of less than 3 K compared to real measurements, confirming the usefulness of simulation for optimizing enclosure design prior to physical testing *(Lin et al., 2022).* Similar dissipation challenges are encountered in 5G/6G infrastructure, where circuit density and limited space require rigorous thermal strategies, including those based on artificial intelligence, linking these systems to compact applications such as communication drones *(Dbouk & Mourad, 2025)*.

Overall, the literature shows that the thermal performance of an electronic enclosure depends on the complex interaction between geometry, material, ventilation, internal convection, component heat flux, and external operating conditions. For drones, where every gram and every centimeter matter, optimal solutions must be lightweight, compact, and energy-efficient. The present work builds on these principles to develop and evaluate a series of airflow optimizations in an electronic enclosure intended for equipment mounted on an agricultural drone, with the objective of achieving a stable thermal regime under real operating conditions.

The objectives of the study are:

1. to evaluate the thermal behavior of the enclosure in its current configuration;
2. to identify areas with thermal stagnation;
3. to test design improvements for airflow optimization;
4. to validate the effect of the proposed solutions on maximum temperature values.

MATERIALS AND METHODS

The analysis of the thermal behavior of the electronic enclosure intended for installation on an agricultural drone was carried out using an integrated approach that combines three-dimensional modeling, definition of material properties, configuration of the operating conditions of the internal components, and execution of an extensive set of CFD simulations in the SolidWorks Flow Simulation environment. The objective was to achieve a representation as realistic as possible of the interaction between the airflow inside the enclosure, heat generation by the components, and heat transfer through the walls, in order to identify critical areas and constructive solutions that contribute to cooling optimization.

Geometric configuration of the enclosure and internal components

The 3D model used was imported in SLDASM format and included the complete enclosure, the upper cover, the mounting base, and all relevant electronic components: the electric pump, the Li-ion battery, the HUB module, two relays, the PCB board, and the supporting structure. The geometry was maintained at full scale to ensure airflow and heat distribution as close as possible to real operating conditions. Internal free spaces, structural cavities, edges, thin walls, and narrow regions were preserved in the model, as they influence the formation of local flow patterns, air stagnation zones, and thermal dissipation paths.

Figure 1 presents the three-dimensional model of the electronic enclosure used in the CFD simulations, including the positioning of all internal components relevant to the thermal analysis. The enclosure is shown in a transparent configuration in order to highlight the arrangement of the elements within the internal volume. On the left side, the electric pump is visible, modeled with complete geometry to reproduce the local heating generated by the internal motor. In the central area, the Li-ion battery is positioned, while on the right side the HUB module (highlighted in green) is located, characterized by high thermal conductivity due to its metallic structure. The relays, the electronic board, and the fastening elements are also visible, all modeled at full scale to accurately capture the interactions between internal convection, thermal conduction, and enclosure geometry. This configuration forms the basis of all thermal simulations, as the spatial distribution of the components directly influences both the formation of internal flow patterns and the accumulation of heat in sensitive areas.

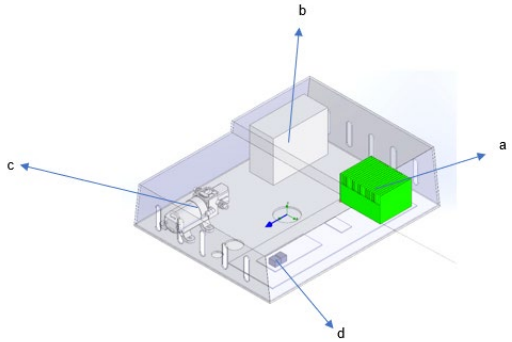


Fig. 1 - Presentation of the main heat-generating components

The enclosure was modeled as a closed volume in its initial configuration, with a single internal space connected to PMMA walls. The components were positioned according to the real configuration used in functional tests: the pump in the central–lower area, the battery on the right lateral side, the HUB module above the control board, and the relays in the lower section. This arrangement generates a complex thermal distribution, as the pump—the component with the highest temperature—is placed closer to the center of the enclosure, while natural convection tends to transport the heated air toward the upper part, where the remaining components are also located.

Figure 2 illustrates the main internal components of the analyzed enclosure, which generate heat during operation of the electronic system mounted on the drone:

a) the HUB, with an aluminum housing, responsible for processing and heat generation due to high electrical power consumption;
b) the 12 V – 22.4 Ah Li-ion battery, which exhibits moderate thermal behavior, mainly influenced by the charge/discharge current;
c) the electric pump, one of the hottest elements during operation, due to the internal motor and mechanical friction;
d) the relay module, an electronic component that accumulates heat during repeated load switching.

a) b) c) d)

Fig. 2 - Presentation of the main heat-generating components

Materials, thermal properties, and justification of selection

To ensure model realism, the materials were defined using real or equivalent thermal properties. The enclosure was considered to be made of PMMA, with low thermal conductivity (approximately 0.19 W/m·K), a characteristic that limits heat transfer to the exterior and promotes internal heat accumulation. This behavior is typical of plastic enclosures used in UAV systems to reduce mass, but it represents a challenge in cooling system design.

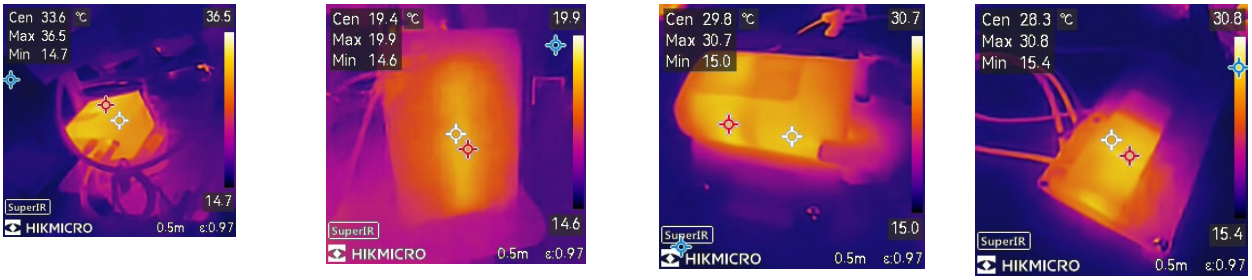
The pump, battery, and PCB elements were defined as ABS, a material commonly used in electronic components due to its good mechanical strength, but which also exhibits low thermal conductivity (approximately 0.17 W/m·K). The HUB was defined as aluminum, since its internal structure includes metallic elements with high thermal conductivity (≈205 W/m·K), allowing more effective natural heat dissipation compared to polymer-based components.

The relays were defined as PA6, a material with moderate thermal conductivity, while the PCB area was characterized using typical properties of glass-fiber-reinforced composite materials, which helps to partially dissipate the heat generated by active electronic components.

Definition of initial thermal conditions and heat sources

The initial temperatures of the components were defined based on the datasheets and operating characteristics of each electronic element. In the CFD simulations, intentionally elevated thermal values were used—100 °C for the pump, 75 °C for the HUB, 65 °C for the battery, and 75 °C for the relays—in order to analyze the behavior of the assembly under extreme thermal scenarios. This temperature set does not reflect real values under normal operation, but rather represents a severe scenario designed to identify potential thermal risk zones, dominant heat transfer paths, and the constructive limits of the enclosure.

Experimental measurements performed on the prototype showed that, during normal operation, the system runs at significantly lower temperatures, with internal components almost never reaching the extreme values introduced in the simulations. The differences between these two datasets are also influenced by different ambient conditions: the experiments were conducted at a temperature of 15–16 °C, which favors heat dissipation, while the simulations used a standard ambient temperature of 23 °C. The values measured during testing will later be integrated into the numerical model for recalibration, so that the simulations reflect as accurately as possible the real thermal behavior of the system under normal operating conditions.



a) b) c) d)

Fig. 3 - Presents the results of thermographic measurements performed on the components during operation

a) The HUB, recording a maximum temperature of approximately 36.5 °C, with a uniform heat distribution.
b) The battery, operating in a steady regime, exhibiting a low temperature of around 19.9 °C.
c) The electric pump, where the maximum measured temperature is approximately 30.7 °C, confirming the internal heating generated by the motor.

d) The relay module, with a maximum temperature of approximately 30.8 °C, highlighting a local heating zone near the active electronic components.

Configuration of the computational domain and boundary conditions

The analysis domain included the enclosure and a surrounding near-field volume with dimensions of 0.42 × 0.16 × 0.52 m. The boundaries were set to ambient conditions with a constant temperature of 23 °C and a static pressure of 101,325 Pa. No imposed velocities were defined inside the domain for the initial scenario, allowing natural convection to develop freely.

All internal walls were considered smooth, without additional roughness, in order to simplify the model without altering the relevant thermal phenomena. Radiative heat transfer was not activated, as the majority of the phenomena of interest occur in the conduction–convection regime.

Configuration of the physical model and the solver

The simulation was configured as transient, with a total duration of 900 s, allowing observation of the stabilization of internal temperatures as heat accumulates and flow patterns develop. The SolidWorks Flow Simulation solver was run using an implicit turbulence model (adaptive k–ε), suitable for confined spaces with limited mixing regions.

Although turbulence inside the enclosure is relatively low in the absence of a fan, the model allows the capture of low-intensity phenomena that occur in areas with temperature and density variations.

Generation and evaluation of the discretization mesh

The initial automatic mesh generated approximately 5,000 cells, with additional refinement around small components, narrow edges, and the enclosure walls. Although relatively compact, the mesh was validated through sensitivity tests, confirming that differences in maximum temperature did not exceed 3% between different discretization levels. This result indicates adequate fidelity for the comparative analysis of subsequent scenarios.

Simulated scenarios and optimization methods:

- Scenario 1 – First simulation series – steady-state regime (no imposed wind): The first set of simulations was performed without imposed air velocities, relying solely on natural convection inside the enclosure. The objective was to observe how heat accumulates when the device operates in a stationary condition, under circumstances similar to static bench tests.
- Scenario 2 – Airflow of 1 m/s: To simulate conditions in which the drone is moving or the device is exposed to a moderate airflow, a velocity of 1 m/s was applied in the Z direction. This value represents a realistic scenario for drones operating at low speed or situations where the enclosure is naturally ventilated through motion.
- Scenario 3 – Airflow of 7 m/s: To evaluate operational limits and behavior under extreme conditions, a velocity of 7 m/s was applied. This value is well above the levels encountered in normal drone applications, but it is useful for observing how convective heat transfer becomes dominant.

RESULTS

The results obtained from the three series of simulations—steady-state conditions, air velocity of 1 m/s, and air velocity of 7 m/s—highlight the way in which internal air circulation influences the temperature distribution inside the electronic enclosure. The analysis enables the identification of critical zones, evaluation of the impact of different convection regimes, and determination of configurations that lead to optimized thermal dissipation. The interpretation of the results is based on the maximum temperatures of the components, internal flow velocity fields, volumetric thermal distributions, and the formation of convective structures.

Results of the steady-state simulation (no imposed wind)

The first simulation investigated the thermal behavior of the enclosure when it operates in the absence of any external airflow, being cooled exclusively by natural convection. This scenario represents the typical bench-use condition, during static tests or when the drone is inactive but the components remain powered.

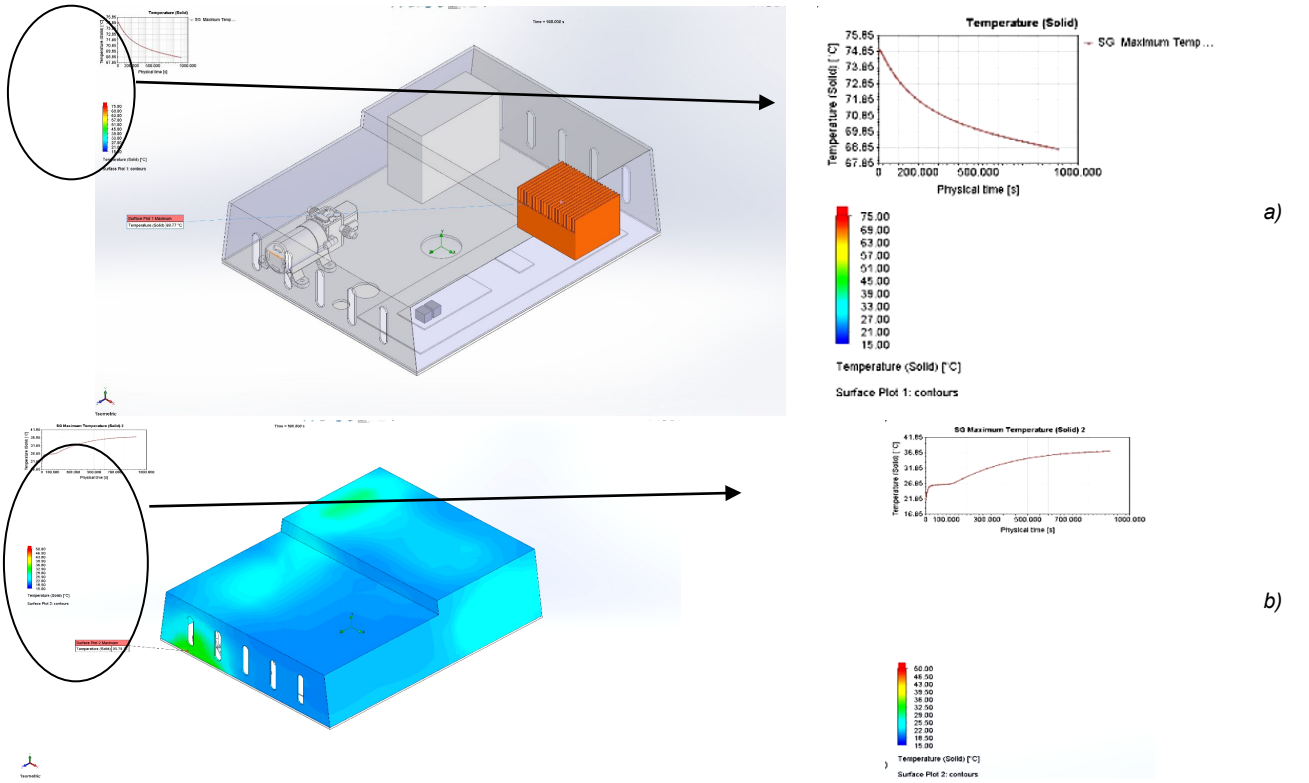


Fig. 4 - Results of the steady-state simulation

a) Temperature distribution of the internal components and evolution of the HUB temperature

Subfigure (a) shows the temperature distribution inside the enclosure under steady-state conditions, without imposed wind. Areas with thermal accumulation are concentrated around the HUB and the pump, as a result of the high initial temperatures used in the analyzed severe scenario. The accompanying graph indicates the evolution of the maximum temperature of the HUB over the simulation time, highlighting a rapid increase in the initial phase, followed by a stabilization trend characteristic of natural convection in a closed volume. This evolution illustrates how the HUB accumulates and dissipates heat in the absence of additional ventilation mechanisms.

b) Temperature distribution on the external surface of the enclosure and its temperature evolution

Subfigure (b) illustrates heat propagation to the exterior of the enclosure through conduction. The hottest areas are found on surfaces located directly above internal components with high thermal loads, while the rest of the enclosure remains at significantly lower temperatures due to the low thermal conductivity of the PMMA material. The corresponding graph presents the evolution of the maximum temperature at the enclosure level over the simulation duration, confirming the achievement of a stable thermal regime, with minor variations after the initial heating phase.

The results indicate a pronounced heat accumulation around the pump, the component defined in the simulation at 100 °C. Due to its central positioning and the low thermal conductivity of the ABS material, the pump generates a significant volume of hot air that rises toward the upper part of the enclosure, where the HUB and relays are located. The HUB, having a metallic body, exhibits a more uniform thermal distribution, but retains heat near the upper enclosure surfaces due to weak air circulation.

The battery shows moderate thermal behavior, being laterally positioned and having a lower thermal contribution. The coldest zones are observed in the lower part of the enclosure and in corners distant from heat sources, indicating a lack of effective internal circulation.

The simulation reveals the presence of several “critical points”:

- the space immediately above the pump,
- the upper area in the vicinity of the HUB,
- the region near the relays, where air stagnation amplifies thermal accumulation.

These hot spots are generated by the limited convective characteristics of the closed enclosure and by the absence of natural pathways for hot air evacuation. Airflow is weakly developed, with the formation of

small convective loops that are insufficient to transport heat efficiently. Hot air rises, accumulates in the upper region, and slowly moves toward the walls without producing significant internal ventilation.

RESULTS OF THE SIMULATION WITH IMPOSED WIND OF 1 m/s

The second simulation applied a constant air velocity of 1 m/s in the Z direction, representing the typical regime when the drone moves slowly or is exposed to a natural airflow. The objective was to observe the effect of a modest flow on thermal dispersion.

Reduction of maximum temperatures

The introduction of external flow generated a visible decrease in the maximum temperatures of all components. Air entering through micro-gaps, joints, and non-sealed areas of the enclosure produces an air-sweeping effect on the internal volume. The reductions are more pronounced in:

- the pump area, where external airflow enhances heat transport,
- the upper part of the enclosure, where thermal accumulation is significantly reduced.

Modification of the thermal distribution

The temperature distribution becomes more uniform, and the differences between “hot spots” and cooler areas are reduced. Air is entrained inside the enclosure, creating a combined convection regime (natural + forced) that promotes heat dissipation. The critical zones identified in the steady-state scenario are mitigated, although they do not completely disappear.

Internal flow characteristics

At 1 m/s, the appearance of internal micro-jets can be observed, directing cooler air toward the hottest components. The flow penetrates through peripheral openings of the enclosure, destabilizing the layers of hot air that, under steady-state conditions, remained trapped in the upper region.

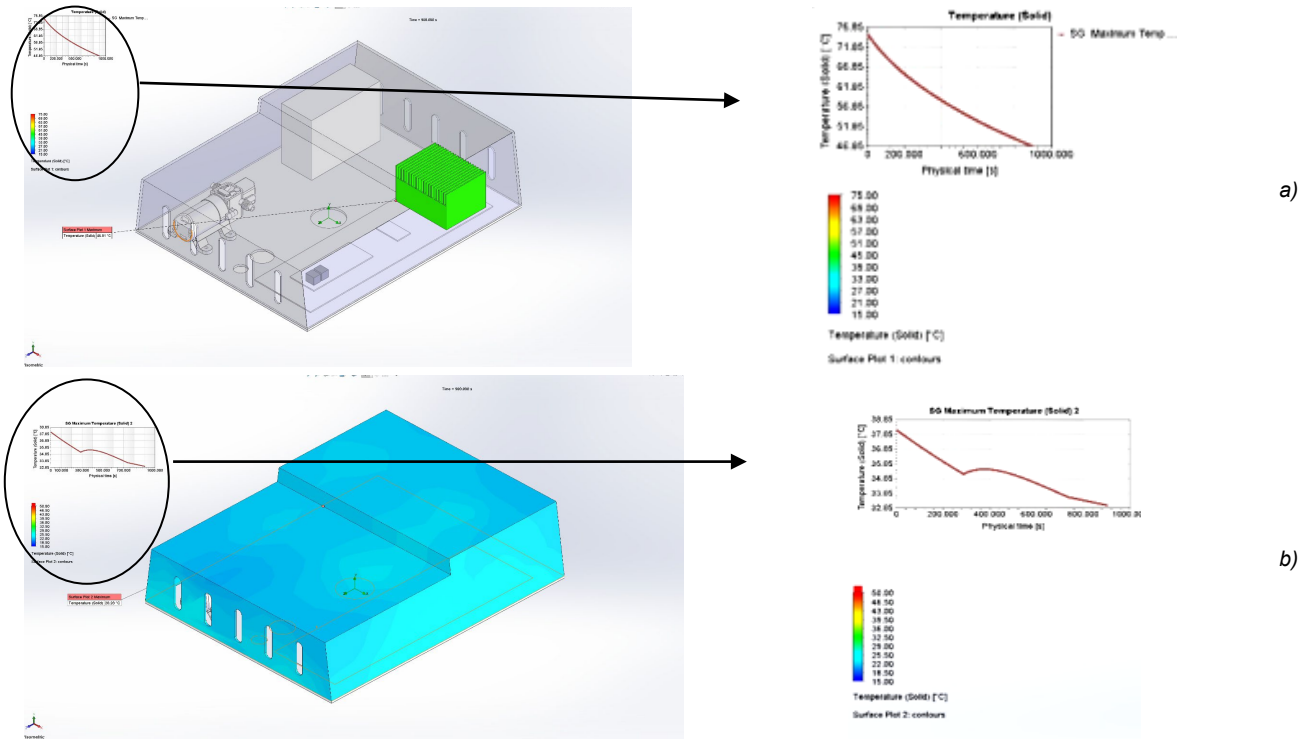


Fig. 5 - Results of the simulation with imposed wind of 1 m/s

Results of the simulation with imposed wind of 7 m/s

The third simulation applied an airflow of 7 m/s, representing an extreme scenario, significantly more intense than real operating conditions. This test allowed the evaluation of the upper limit of cooling by convection.

Dominance of forced convection

At this velocity, the thermal distribution is completely different:

- internal temperatures drop sharply,
- hot spots almost completely disappear,
- temperature differences between components become minimal.

Forced convection dominates all other heat transfer mechanisms, and hot air is efficiently extracted from the enclosure.

Complete temperature uniformity

Stratified thermal layers are eliminated. Cold air enters and exits rapidly, resulting in intense and uniform circulation. This regime highlights the potential for enclosure optimization by introducing vents or miniaturized fans capable of generating comparable airflow.

Internal cold zones

The appearance of significantly cooler zones in the lower part of the enclosure can be observed, demonstrating that the entire enclosure is efficiently ventilated. The temperature differences between the pump and the other components become small, suggesting that intense external cooling prevents thermal accumulation even in elements with high thermal loads.

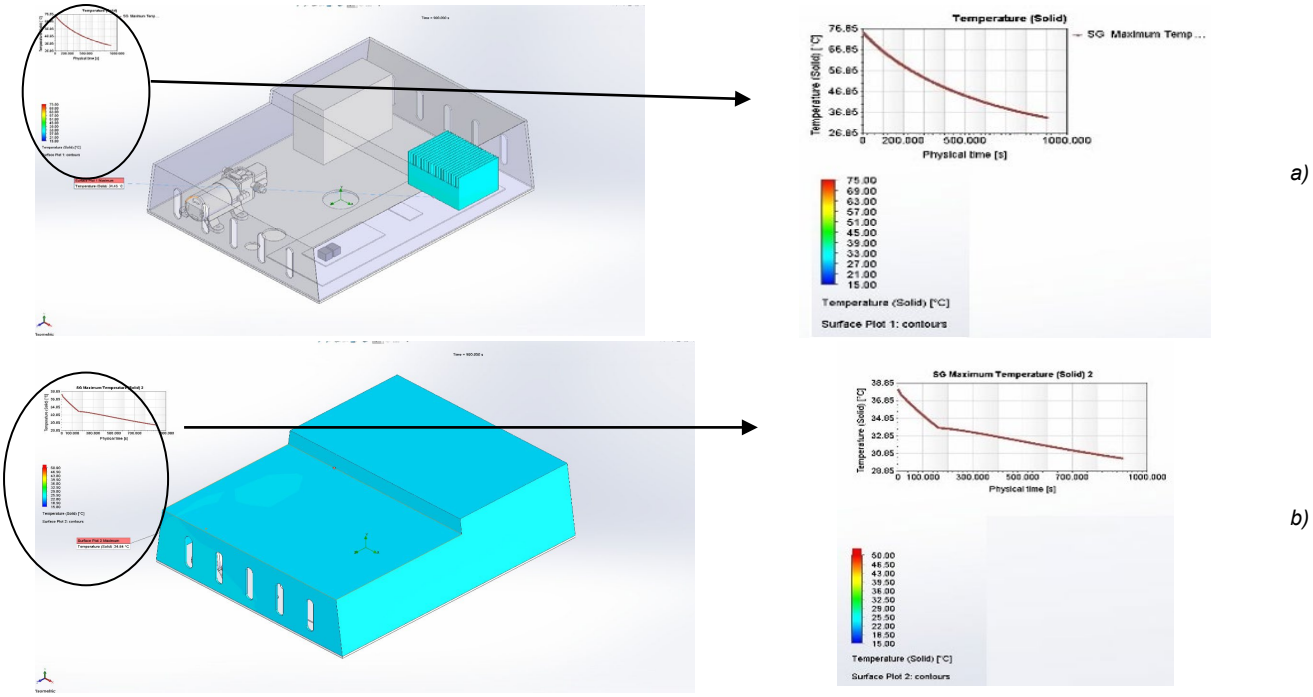


Fig. 6 - Results of the simulation with imposed wind of 7 m/s

Table 1

Comparison of results between scenarios (steady-state, 1 m/s, 7 m/s)

Analyzed parameter	Steady-state scenario (0 m/s)	1 m/s scenario	7 m/s scenario
Maximum HUB temperature	Highest value; rapid heating and slow stabilization	Significantly reduced due to moderate flow; improved dissipation	Strongly reduced; much lower values; convection dominated by external flow
Maximum pump temperature	High, strongly influencing internal air	Moderate–high reduction; external air partially removes heat	Major reduction; cold air immediately extracts generated heat
External enclosure temperature	Well-defined hot areas on the surface; weak dissipation through PMMA	Hot areas reduced; more uniform thermal distribution	Very uniform temperatures; enclosure remains cool over almost the entire surface
Formation of internal hot spots	Extensive zones in the upper part and around the pump	Clear reduction; air stagnation decreases	Almost eliminated; airflow distribution becomes uniform
Natural internal convection	Very weak; small convective loops	Combined natural + forced convection; improved circulation	Strongly forced convection; air circulates intensively through micro-gaps and inside
Temperature uniformity	Highly heterogeneous temperatures with large spatial differences	Improved uniformity compared to steady-state	High uniformity; minimization of thermal gradients
Temperature stabilization over	Slow; visible thermal accumulation	Accelerated stabilization due to airflow	Rapid stabilization; low temperatures from early stages

time			
Thermal risk for components	High in HUB–pump areas	Moderate; significantly reduced compared to steady-state	Minimal; ideal cooling conditions via convection
Thermal dissipation efficiency	Low	Medium–high	Very high

Correlation with experimental measurements

Thermographic measurements performed on the prototype indicated significantly lower maximum temperatures:

- HUB: 36.5 °C;
- Pump: 30.7 °C;
- Relays: 30.8 °C;
- Battery: 19.9 °C.

These values confirm that the extreme scenarios used in the simulations do not occur under normal operation, but they are useful for assessing thermal safety margins. The transient behavior observed in the experiments (initial temperature rise followed by stabilization) is consistent with the simulated evolution for the steady-state regime, which validates the methodological approach and confirms that CFD models can reliably reproduce relative thermal distributions.

CONCLUSIONS

The thermal analysis carried out on the electronic enclosure intended for installation on an agricultural drone demonstrates that the internal geometry, the materials used, and the external aerodynamic conditions decisively influence the temperature distribution within the assembly. CFD simulations performed in three distinct scenarios—steady-state regime, airflow at 1 m/s, and airflow at 7 m/s—highlighted different evolutions of the thermal field, enabling clear identification of critical zones and the mechanisms leading to thermal accumulation.

In the steady-state regime, characterized by weak natural convection and the absence of imposed airflow, the system develops extensive stagnation zones, particularly around the pump and in the upper part of the enclosure. Maximum temperatures reach elevated values, accentuated by the low thermal conductivity of the PMMA material, which confirms the limitations of passive cooling in closed enclosures. The simulations revealed the formation of minor convective loops, insufficient for efficient heat transport, leading to the appearance of hot spots that may accelerate the degradation of electronic components.

The application of an external airflow of 1 m/s visibly improves thermal dissipation, homogenizes the temperature field, and reduces internal gradients. Convection becomes mixed (natural + forced), allowing a reduction in peak temperatures and attenuation of critical zones. This regime corresponds to realistic operating scenarios of a drone in slow flight, where airflow dynamics naturally contribute to cooling electronic components.

At 7 m/s, forced convection becomes the dominant mechanism, producing a sharp temperature decrease, elimination of hot spots, and near-complete uniformity of the thermal field. Although this value exceeds typical flight conditions, the simulation demonstrates the theoretical limits of the system and provides essential information for enclosure optimization aimed at integrating active ventilation solutions.

Comparison of the CFD results with real measurements performed on the prototype confirms that the thermal regime of the system during operation is significantly lower than the extreme simulated scenarios. Nevertheless, these severe scenarios are necessary to evaluate system behavior under limit conditions and to design robust constructive solutions. The transient behavior observed in real tests aligns with the steady-state simulation results, validating the fidelity of the numerical model and enabling extension of the study toward geometric and aerodynamic optimizations.

Overall, the results indicate that introducing airflow-guiding elements, optimized vents, or even a micro-fan can significantly reduce thermal risk, increase electronic system stability, and improve assembly reliability under real flight conditions. The analyzed enclosure shows considerable potential for improvement through minimal interventions in geometry and ventilation.

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THE POTENTIAL OF OIL EXTRACTED BY COLD PRESSING HEMP SEEDS FOR FOOD USE
/
POTENȚIALUL ULEIULUI EXTRAS PRIN PRESAREA LA RECE A SEMINȚELOR DE CÂNEPĂ PENTRU UZ ALIMENTAR

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ABSTRACT
There is an increasing global interest in the use of plant-based proteins, which supports the creation of protein-rich foods capable of replacing animal proteins in the human diet. Thus, the negative impact that intensive animal farming has on the environment is reduced. Industrial hemp (Cannabis sativa L.) is a versatile plant, widely used throughout history for various purposes (medicinal, food and other uses). Hemp seeds contain a significant amount of fiber, vitamins, minerals and phenolic compounds, having approximately 30% oil and 25% protein in their composition. The oil extracted from hemp seeds is appreciated for its nutritional values, offering numerous health benefits. Oils extracted by cold pressing from seeds have become popular in commercial markets, being considered natural and safe products for consumption. This paper presents a series of applications of hemp seed oil in the food industry.

REZUMAT
Se observă o creștere a interesului global pentru utilizarea proteinelor de origine vegetală, ceea ce susține crearea de alimente bogate în proteine capabile să înlocuiască proteinele de origine animală din dieta umană. Astfel, se reduce impactul negativ pe care creșterea intensivă a animalelor îl are asupra mediului. Cânepa industrială (Cannabis sativa L.) este o plantă versatilă, utilizată pe scară largă de-a lungul istoriei în diverse scopuri (medicinale, alimentare și alte utilizări). Semințele de cânepă conțin o cantitate semnificativă de fibre, vitamine, minerale și compuși fenolici, având aproximativ 30% ulei și 25% proteine în compoziția lor. Uleiul extras din semințele de cânepă este apreciat pentru valorile sale nutriționale, oferind numeroase beneficii pentru sănătate. Uleiurile extrase prin presare la rece din semințe au devenit populare pe pieţele comerciale, fiind considerate produse naturale și sigure pentru consum. Această lucrare prezintă o serie de aplicații ale uleiului de semințe de cânepă în industria alimentară

INTRODUCTION
Hemp (Cannabis sativa L.), an annual herbaceous plant, is considered one of the oldest cultivated plants in history. It represents a culture that combines multiple functionalities, being sustainable and with minimal impact on the environment. Hemp is useful in various fields, from agriculture and plant remediation to the food and animal feed sector, cosmetics, construction and the pharmaceutical industry (Oo*mah, B.D. et al., 2002; Cerino, P. et al., 2020; Crini, G. et al., 2020; Farinon, B. et al., 2020*). Throughout its history, hemp has generated numerous controversies. It reached its peak between the late 1800s and early 1900s, when it was used as the main ingredient for drying oil in the dyeing, textile, and fuel industries. However, the restrictions imposed on all types of cannabis by the Marijuana Taxation Act of 1937 have led to the suspension of commercial hemp cultivation in most global regions (Le*onard, W. et al., 2020*).

Hemp (*Cannabis sativa L.)* It has recently experienced a significant recovery, and the attraction for its use in various fields, including the food industry, is continuously increasing. Given its extraordinary nutritional properties, hemp has recently become an increasingly sought-after element in the manufacture of high-quality food and nutritional supplements. Among them, it is important to mention cold-pressed hemp seed oil, which, in relation to its specific sensory quality and nutritional characteristics, is certainly one of the most widespread (*Mandrioli, M. et al., 2023*).

The use of hemp ingredients in food is regulated by their low concentrations of THC and CBD. There are various restrictions for these substances in hemp foods, varying from country to country and between different legislative areas. As an example, the THC level allowed for hemp seed oil used in the food industry, in Australia is 10 mg/kg, in the EU 7.5 mg/kg and in the US 10 mg/kg (Burton, R.A. et al., 2022). The recent

application of hemp protein in food processing reveals its unique properties. In particular, in recent studies, its amino acid-rich composition and high sulfhydryl (-SH)/disulfide (SS) ratio provide a glimpse into its distinctive characteristics useful in food processing (*Xu, Y. et al., 2022*).

Hemp is also cultivated throughout Europe. The cultivated area in the EU increased significantly from 19,970 to 34,960 hectares between 2015 and 2019. The global industrial hemp market was estimated at USD 4.13 billion in 2021 and is expected to grow at a compound annual growth rate (CAGR) of 16.8% between 2022 and 2030 (Yano, H. et al., 2023). *Cannabis sativa L.* it has a unique nutritional composition that is high in protein and low in carbohydrates *(Mohd Fairulnizal, M.N. et al., 2015*). The seeds contain more than 30% oil, 25% protein, dietary fiber, vitamins, and minerals (*Mandrioli, M. et al., 2023*).

Hemp seed oil is distinguished by a high level of terpenes, which influence the taste of cannabis food. Also, the terpenes in hemp have anti-inflammatory, anticancer, and antioxidant roles, and research has shown that they amplify the therapeutic effects of Cannabidiol (CBD) (*Sirangelo, T.M. et al., 2025*).

MATERIALS AND METHODS

Cold pressing is a mechanical technique that relies on pressure, pressing oil grains with force, and extracting the oil. Processed at a lower temperature, the oil does not alter its properties (high phenolic content, flavor and nutritional value). Cold-pressed oils are extracted from the seeds and fruits of oilseeds with an oil content of more than 15%. It is made using a hydraulic press or with an ejector (screw type) equipped with a cooling system. This method is relatively easy and inexpensive (*Khoddami, A. et al., 2014; Chandra, S. et al., 2020*). The choice of extraction technique and temperature for storage proved essential to preserve the quality of the oil. Thus, although with lower extraction efficiency, hydraulic press extraction provides stable oil with low PUFA losses at 55 °C, and the optimal storage temperature is below 45 °C (*Senphan, T. et al., 2025*).

Consumers are increasingly attracted to cold pressing as an environmentally friendly, chemical-free oil extraction method that produces oil with superior nutritional qualities and unique flavor (retains several of the beneficial components of the seeds, including valuable PUFAs and bioactive substances). While cold pressing offers numerous benefits, its main drawback is its relatively low extraction efficiency, which leaves 8%-14% of the total oil in the cake (*Fathollahy, I. et al., 2024*).

Cold-pressed seed oils have become more commercially popular because they are considered natural and safe products for use in food. This process preserves several of the beneficial components of the seeds, including valuable PUFAs and bioactive substances, while minimizing degrading changes to the oil. A notable disadvantage of cold-pressed oil is the low yield potential of 60-80% extractable oil (*Rupasinghe, H.P.V. et al., 2020*).

The literature presents evidence necessary to define the quality of cold-pressed hemp oil according to the basic criteria of the Codex Alimentarius, and some related considerations, such as seed preservation methods, fundamental variables of the production process. In order to guarantee consumers the safety of the edible oil obtained, the legal limit (7.5 mg/kg) is recommended, expressed as the sum of Δ9 – tetrahydrocannabinol (acidic plus neutral form) (*Mandrioli, M. et al., 2023*).

Another point of interest in technological processes in the food industry is the color of products derived from hemp seeds. Color plays a preeminent role in consumer acceptance and, consequently, in the choice of a food. In the case of oils, color could represent an index of good manufacturing practice, a guarantee of quality and authenticity and, last but not least, of the right storage conditions (*Tura, M. et al., 2023; Tănase Apetroaei, V. et al., 2024*).

The color measurement of hemp seed oil samples was performed using a CIELAB color system. Figure 1 shows samples of hemp seeds and pressed seed oils (*Spano, M. et al., 2020*).

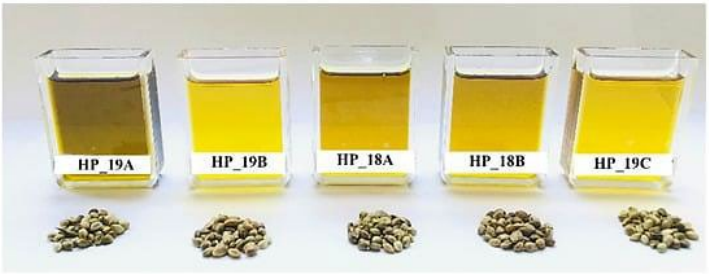

Fig. 1. Hemp seeds and cold-pressed hemp seed oils. Group 1 oils (HL_18A, HL_18B) and group 2 oils (HL_19A, HL_19B, HL_19C) *(Spano, M. et al., 2020)*

Virgin hemp seed oil produced only by screw pressing has a green color due to chlorophyll co-extracted with the oil (Burton, R.A. et al., 2022). The chemical composition of hemp oil and parameters such

as acidity, peroxide index and absorbency are essential for its qualification for human consumption. Differences in hemp seed harvesting and processing methods can significantly influence the content of bioactive substances (Kaur, G. et al., 2023).

RESULTS

Extensive research that has designated hemp as perhaps the most studied plant in human history has led to the identification of hundreds of different compounds with potential biological activity, including more than 120 terpenoids, 100 cannabinoids, 50 hydrocarbons, 34 glycosidic compounds, 27 nitrogenous compounds, 25 non-cannabinoid phenols, 22 fatty acids, 21 simple acids, 18 amino acids, 13 simple ketones, 13 simple esters and lactones, 12 simple aldehydes, 11 proteins, glycoproteins and enzymes, 11 steroids, 9 trace elements, 7 simple alcohols, 2 pigments, as well as vitamin K (Cerino, P. et al., 2021).

Since ancient times, hemp has been cultivated to provide nutritional and medicinal benefits. Although government regulations have suppressed the cultivation and scientific research of industrial hemp in the past, with recent legalization with strict production regulations, hemp has been shown to have viable, value-added food and nutraceutical applications (fig. 2), (Rupasinghe, H.P.V. et al., 2020).

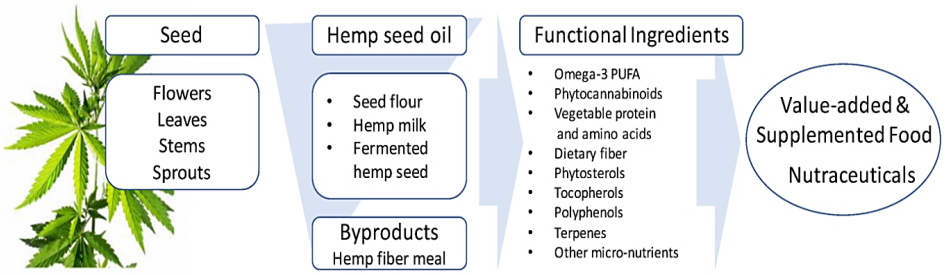

Fig. 2. Advanced value-added technologies can drive value-added innovation to use industrial hemp to introduce a wide range of functional food ingredients and nutraceuticals *(Rupasinghe, H.P.V. et al., 2020)*

Hemp oil has a pleasant taste and various advantages over other vegetable oils, exhibiting high levels of provitamin A, vitamin E, and fat-soluble minerals, especially phosphorus, potassium, magnesium, sulfur, and calcium (Montserrat-De La Paz, S. et al., 2014). Provitamin A, including β-carotene, can be easily converted into vitamin A in the human body. These fat-soluble vitamins A and E are trace amounts of organic substances that people typically ingest from food, especially vegetable oils, to maintain normal physiological functions (Xu, Y. et al., 2021).

Related to the fatty acid composition of hemp seed oils, the predominance of polyunsaturated fatty acids (PUFAs) among unsaturated fatty acids is shown, ranging from 74 to 76%, table 1 (Islam, M. et al., 2023).

Table 1

Fatty acid composition expressed as a percentage of total fatty acids (%) in cold-pressed hemp seed oils of the Henola variety *(Islam, M. et al., 2023).*

Fatty Acids	*Henola* Cultivar Oil Samples				
	Group 1		Group 2		
	HL_18A	HL_18B	HL_19A	HL_19B	HL_19C
∑SFA	10.91 ^{b} ± 0.03	10.65 ^{a} ± 0.06	11.03 ^{b} ± 0.01	10.56 ^{a} ± 0.06	10.92 ^{b} ± 0.12
∑MUFA	13.4 ^{b} ± 0.00	12.58 ^{a} ± 0.00	14.59 ^{d} ± 0.00	13.33 ^{b} ± 0.02	14.18 ^{c} ± 0.06
∑PUFA	75.45 ^{c} ± 0.02	76.57 ^{d} ± 0.06	74.14 ^{a} ± 0.00	75.76 ^{c} ± 0.01	74.67 ^{b} ± 0.18
∑EFA	73.43 ^{b} ± 0.04	74.33 ^{c} ± 0.06	72.43 ^{a} ± 0.01	73.72 ^{b} ± 0.04	72.68 ^{a} ± 0.19
UFA/SFA	8.143	8.371	8.048	8.440	8.314
n-6/n-3	3.094	2.917	1.896	2.799	3.097

^{ABCD}—values are averages ± standard deviations of two measurements (n = 2); different superscript letters indicate significant differences ($p \leq 0.05$) in the rows. ∑SFA—total saturated fatty acids. ∑MUFA—total monounsaturated fatty acids. ∑PUFA—total polyunsaturated fatty acids. ∑EFA—total essential fatty acids. UFA/SFA - the ratio of total unsaturated fatty acids to total saturated fatty acids. Group 1 oils (HL_18A, HL_18B) and group 2 oils (HL_19A, HL_19B, HL_19C)

In addition, hemp seed oil contains a significant amount of stearidonic acid (between 0.5 and 2%), which has a positive impact on human health. It has become clear that stearidonic acid (SDA) increases

eicosapentaenoic acid more effectively than α-linolenic acid (ALA) (T*ura, M. et al., 2022*). A number of recent studies highlight the potential of stearidonic acid (SDA) as an environmentally friendly and sustainable alternative to fish-derived omega-3 PUFAs (*Baker, E.J. et al., 2025*). The high level of polyunsaturated fatty acids in hemp seed oil means that it can be used as a nourishing oil for salad dressings, but is not suitable for frying in oil due to the high level of unsaturation in the oil (*Zahari, I. et al., 2020; Cherney, J. & Small, E., 2016*).

Hemp seed oil (HSO) is touted as one of the few vegetable oils that contains about 80% polyunsaturated fatty acids in a perfect 3:1 ratio of ω-6 to ω-3, suggesting that it is optimal for human nutrition due to its potential health benefits. An unfortunate paradox of HSO lies in its desaturation, which makes it both highly nutritious and chemically unstable (*Occhiuto, C. et al., 2022*).

At the Nutrition Laboratory of Massey University, New Zealand, a compositional analysis of the body oil fraction of hemp seeds was carried out, such as moisture content, fat content, crude protein content and ash content, and the values obtained are described in the table ...

Table 2

Approximate composition of hemp seed oil bodies (*Garcia, F.L. et al., 2021*)

Parameter	Composition (%, wet base)
Humidity	22.80 ± 2.09
Fat	79.30 ± 2.78
Crude Protein	1.50 ± 0.22
Ash	0.20 ± 0.01

The results of an analytical study present (Cannabis sativa L.) as an oilseed crop with valuable potential for Uzbekistan.Table 3 shows the value of different macro-trace elements in unrefined cannabis oils, (determined by IPP-OES) (*Mamadaliev, A.N. et al., 2023*).

Table 3

Elemental composition in industrial hemp seed oil (Cannabis sativa L.)* *(Mamadaliev, A.N. et al., 2023)*

Constituent mg//100g)	Sample 1	Sample 2	Sample 3
Calcium (Ca)	1.10 ± 0.02	1.25 ± 0.03	1.80 ± 0.02
Iron (Fe)	0.40 ± 0.001	0.90 ± 0.002	0.60 ± 0.001
Magnesium (Mg)	0.30 ± 0.001	0.57 ± 0.002	0.70 ± 0.002
Cadmium (Cd)	-	-	-
Sodium (Na)	0.08 ± 0.001	0.15 ± 0.004	0.10 ± 0.003
Zinc (Zn)	0.06 ± 0.001	0.11 ± 0.002	0.09 ± 0.001
Mercury (Hg)	-	-	-

*The table represents average values of the standard deviation for three grades of oils, technical hemp (Cannabis sativa L.), analyzed individually in three samples.

The interest in hemp polyphenols and their antioxidant characteristics is a beginning for the use of processing methodologies that facilitate the release of phytochemicals from the hemp fiber structure, which, through various chemical interactions, restrict their intestinal absorption. The extraction of polyphenols from seeds during the processing process could enhance the value of hemp-based products and their appeal to human health. Micro- and nano-encapsulation could protect the polyunsaturated fatty acids in hemp seed oil from oxidation (*Rizzo, G. et al., 2023*).

The presence of antioxidant components, such as tocopherols, increases the nutritional value, healthy properties of hemp seed oil and its shelf life. In fact, tocopherols act both as natural antioxidants against oxidative oil damage and as vitamin E in the body. In contrast, the oxidation process can be catalyzed by the presence of a substantial amount of chlorophyll in hemp seed oil, which is also extracted through the cold pressing process (*Tura, M. et al., 2023*).

Table 4

Composition of tocopherol in cold-pressed hemp seed oil (various significant figures are indicated in the table according to those reported by the authors, and for the uniformity of the results in the table, all values have been converted to mg/kg).

Tocopherol	Rovellini et al. (2013)	Kostadinovic et al. (2015)	They are et al. (2018)	Blasio et al. (2020)	Tour et al. (2022)	Eye et al. (2022)	Tour et al. (2023)	Allay et al. (2025)
			Cv.Fedora		Cv.Futura 75			

	(mg/kg)	(mg/kg)	(mg/kg)	(mg/kg)	(mg/kg)	(mg/kg)	(mg/kg)	(mg/kg)
α-tocopherol	37	17	2.7	3.5-77.6	38.73	39.2-47.7	John 14:6-53	34.38
β-tocopherol		2	-	3.7-5.8	-	0.1-2.1	-	-
ɣ-tocopherol	858(*)	649	5.0	625.3-1013.2	794.66	774.3-924.5	594-967	348.02
δ-tocopherol	33	25	-	14.0-35.1	29.22	3.2-40.2	19.6-50.3	28.44
Total (mg/kg)	928	697	-	655.0-111.08	-	816.9-1014.5	-	-

The literature highlights the presence of cannabinoids in HSO, and the most representative compounds are CBDA, CBD, Δ9-THC and Δ9-THCA. Some authors have also indicated the presence of CBDA, CBG, and CBN, (Table 5).

Table 5

Cannabinoid composition of cold-pressed hemp seed oil (different significant figures are indicated according to what the authors reported, and for the uniformity of the results in the table, all values have been converted to mg/kg) ***(Mandrioli, M. et al., 2023)***

Cannabinoids	(mg/kg)	(mg/kg)	(mg/kg)	(mg/kg)	(mg/kg)
CBDA	4.25-91.6	-	-	<LOQ 821.1	180
CBD	ND-22.2	10	-	<LOD - 1056	
CBDV	-	-	-	<LOQ - 75.39	
CBG	-	-	-	<LOD - 1,381	
CBN	-	-	-	<LOQ -12.05	
Δ9-THC	ND-5.29	ND	11-117	<LOD -1.804	
Δ9-THCA	ND-5.0	-	-	<LOQ - 9,462	
Δ9-THC+Δ9-THCA	ND-10.30	-	-	-	

The information obtained may be relevant for the management of any stage of the technological production process and, in particular, for the stage of collection, storage and extraction of seeds, to maintain the sensory and nutritional characteristics of the resulting oil and to achieve high and harmonized quality in the market **(***Mandrioli, M. et al., 2023*).

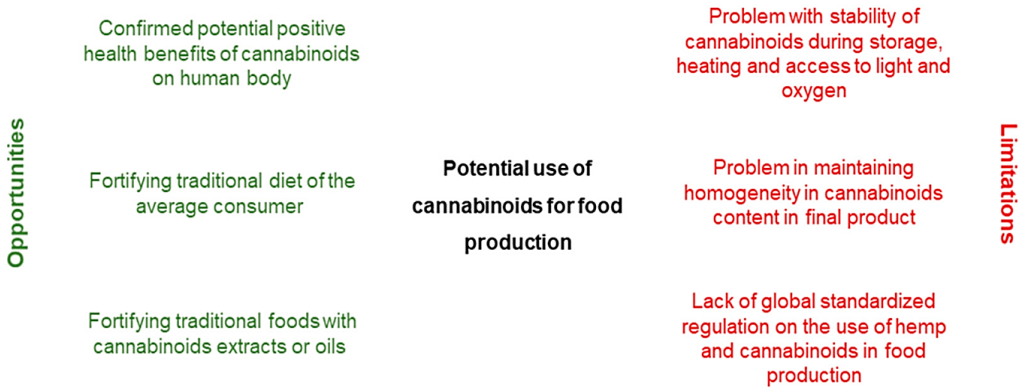

Fig. 3 Main opportunities and limitations that may impact the potential use of cannabinoids in food production *(Kanabus, J. et al., 2021)*

Knowing the vulnerability of hemp seed oil to rancidity, understanding the changes that occur during the storage of hemp oil under various conditions is essential when evaluating its potential use in the food industry. Long storage times and incorrect storage conditions can lead to the degradation of CBDA into CBD (*Kanabus, J. et al., 2021*).

Organic hemp (Cannabis sativa L.) could create opportunities for a regional industry dedicated to the cultivation and processing of cereals and gluten-free foods, (figure 4). These foods are sought after by

people suffering from celiac disease or enteropathy caused by gluten, conditions that affect almost 1% of the world's population. In addition to this, the type of "healthy" diet is becoming increasingly popular among consumers, being more and more frequently integrated into the daily diet, either in the form of a supplement or used directly in cake recipes, bread prepared from hemp flour (Cannabis sativa L.) and in the use of oil extracted from hemp seeds (*Capcanari, T.N. et al., 2024*).

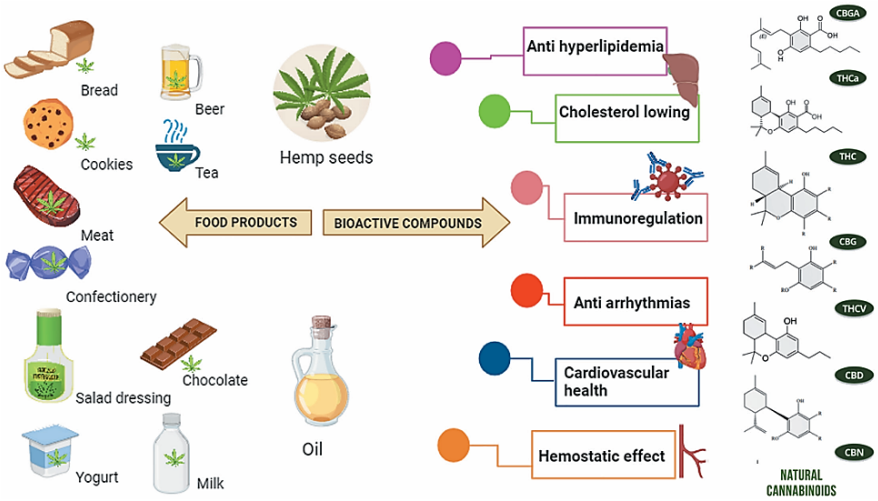

Fig. 4. Food products infused with hempseed sources and their influence *(Capcanari, T.N. et al., 2024)*

In addition to their use in human food, hemp seeds and the oil extracted from them are excellent resources for animal feed, Table 6 (*Xu, Y. et al., 2021*).

Table 6

Applications of Hemp Seed and Oil in Animal Feed *(Xu, Y. et al., 2021)*

Hemp products	Animal	Main conclusions
Hemp seed oil	Carpathian goats	No change in plasma cholesterol, triglyceride or phospholipid concentrations or alanine aminotransferase or γ-glutamyltransferase activities, but total plasma lipid concentration was increased.
Hemp seed oil	Pig	Significantly altered composition of fatty acids in milk, with a decrease in saturated fatty acid concentrations and an increase in polyunsaturated fatty acids and a significantly higher amount of ALA deposited in meat.
Hemp seeds and hemp seed oil	Hen	Increased omega-3 polyunsaturated fatty acid content and increased intensity of egg yolk color, but no adverse effects on the sensory profiles of boiled eggs

CONCLUSIONS

Industrial hemp (Cannabis sativa L.) is a multifunctional crop with a wide spectrum of applications, providing food, fiber and nutraceutical substances. Hemp seed oil is recognized for its outstanding nutritional properties and beneficial to health. These attributes are due to the complex biological composition, from cannabinoids and polyunsaturated fatty acids (PUFAs) to polyphenols, proteins, minerals, and vitamins.

Another positive aspect is the reduced carbohydrate composition. These compounds provide a sustained potential to hemp seed oil in the food industry. For example, the researchers highlighted the yield of stearidonic acid (SDA) as an environmentally friendly and sustainable alternative to fish-derived omega-3 PUFAs. Interest in polyphenols from hemp seed oil is growing due to their antioxidant characteristics.

Hemp oil has a pleasant taste and various advantages over other vegetable oils, exhibiting high levels of provitamin A, vitamin E, and fat-soluble minerals, especially phosphorus, potassium, magnesium, sulfur, and calcium.

In addition to their use in human food, hemp seeds and the oil extracted from them are excellent resources for animal feed. Oil extracted from cannabis seeds is sensitive to the rancidity process, so it is vital to understand the changes that occur during storage under various conditions when considering its use in the food sector.

The analysis of the scientific literature has shown that, from a nutritional point of view, cold-pressed hemp seed oil has the necessary value for its integration into functional foods, in the context of sustainability, and encourages further research in order to obtain innovative products.

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RESEARCH ON THE FORTIFICATION OF PASTRY PRODUCTS WITH POWDER OBTAINED FROM WINE BY-PRODUCTS
/
CERCETĂRI PRIVIND FORTIFIEREA PRODUSELOR DE PATISERIE CU PULBERE OBȚINUTĂ DIN SUBPRODUSE VINICOLE

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ABSTRACT
Grape pomace is a mixture of skins, seeds, and residual grape pulp generated during the winemaking process, and is the most significant by-product of vinification. It represents an abundant and valuable source of polyphenolic compounds. These polyphenols exhibit a wide range of bioactivities, including antioxidant, anti-inflammatory, and anticancer effects. This study presents the results of research aimed at developing a pastry product fortified with powder obtained from winemaking by-products of the Pinot Noir grape variety. Three fortification levels (3%, 6%, and 9%) were applied during the production process. A pastry product with superior sensory qualities (appearance, taste, and aroma), high nutritional value, and antioxidant potential was successfully developed.

REZUMAT
Tescovina de struguri reprezintă un amestec de piețițe, semințe și urme de pulpă de struguri, rezultat după obținerea vinului. Tescovina de struguri este cel mai important reziduu după vinificație și este considerată o sursă foarte abundentă pentru extracția unei game largi de polifenoli. Acești polifenoli prezintă o varietate de bioactivități, cum ar fi antioxidante, antiinflamatorii și anticancerigene. În această lucrare sunt prezentate rezultatele cercetărilor întreprinse pentru realizarea unui produs de patiserie, fortifiat cu pulbere din suproduse vinicole, soi Pinot Noir. Astfel pentru obținerea produselor au fost aplicate trei nivele de fortifiere: 3%, 6% și 9%. A fost obținut un produs de patiserie cu calități senzoriale superioare (aspect, gust și aromă), valoare nutrițională ridicată și potențial antioxidant.

INTRODUCTION

World production of fresh grapes in 2024 is estimated at 77.7 mt, showing 3.7% increase compared to 2023. Fresh grape production has stabilised since 2013. China is by far the first producer with 17.0 mt, followed by Italy (7.3 mt), and the USA (6.4 mt) (*OIV Statistical Brief: Wine, Table Grapes & Dried Grapes in 2024*). Following the winemaking process, significant quantities of winemaking by-products (grape stalk, grape

skins, grape seeds, traces of pulp) are produced. It is estimated that the production of 100 L of white wine results in about 30 kg of winemaking by-products *(Mendes et al., 2013).*

Grape pomace represents a mixture of skins, seeds and traces of grape pulp, resulted after the wine is obtained. These residues are generally underestimated and used in animal feed (with low nutritional value), transformed into a fertiliser and even discarded in the environment with all the problems that this involves (an increase of soil acidity, phytotoxicity, production of methane gas, among other problems) (*Fontana et al., 2013).*

However, grape pomace is the most important residual after wine making, and it is considered to be a very abundant source for the extraction of a wide range of polyphenols. These polyphenols exhibit a variety of bioactivities, such as antioxidant, anti-inflammatory, and anti-cancer. They are also beneficial in alleviating metabolic syndrome and regulating intestinal flora, etc. These health effects are most likely attributed to polyphenol metabolites, which are formed from grape pomace phenolic compounds following complex metabolic processes in vivo. (*Yanget al., 2024*).

Therefore, it is very important their recovery from this food matrix and use them in the composition of food products, as preservatives, antioxidants, colorants or fortifying agents. *Catana et.al. (2020)* evaluated the biochemical composition of the flour obtained from winemaking by-products are noted for their vitamin C content (18.25-25.75 mg/100 g) and total polyphenol content (57.45-258.75 mg GAE/g). Also, due to their content in bioactive compounds, these powders have antioxidant capacity: 9.98-46.12 mg TE/g. Flours obtained from winemaking by-products can be regarded as functional ingredients and can be used to fortify food products (bakery and pastry products, especially) in order to increase the nutritional value and their antioxidant capacity.

In this paper are presented the results of the research undertaken to the fortification of pastry products with powder obtained from wine by-products. The fortification process led to the increase of the nutritional values and the antioxidant potential of the products.

MATERIALS AND METHODS

The product composition and the proposed technological solutions were designed to obtain a bakery product with superior sensory qualities (appearance, taste, and aroma), high nutritional value, and antioxidant potential.

Thus, in addition to the powder obtained from winemaking by-products of the *Pinot Noir* variety, other nutritionally valuable ingredients were used, including wheat flour type 000, brown sugar, Bourbon vanilla sugar, whole milk with 3.5% fat content, butter with 65% fat, eggs, Topoloveni plum jam, etc. The powder obtained from winemaking by-products of the Pinot Noir variety was supplied by National Research & Development Institute for Biotechnology in Horticulture Stefanesti-Argeș.

In order to obtain the fortified bakery products, three fortification levels were applied: 3%, 6%, and 9%. In parallel with the fortified bakery products, a control sample was prepared as follows: CSV_C (control), CSV_V1 (3%), CSV_V2 (6%), and CSV_V3 (9%).

Fig. 1- The product "Croissant fortified with grape pomace powder"

For the qualitative characterisation of the product "Croissant fortified with grape pomace powder" were used standardized methods and developed and validated methods in IBA Bucharest. The moisture content was determined according to the AACC 44-15A method. Protein content was determined by the Kjeldahl method with a conversion factor of nitrogen to protein of 6,25 (AOAC Method 979.09, 2005). Fat content was determined according to AOAC Method 963.15, ash content according to AOAC Method 923.03 (AOAC, 2005) and AOAC 985.29 (total dietary fiber). Total carbohydrate content (%) was estimated by subtracting water, fat, protein and ash content from 100%. The energy value calculation (kcal/100 g and kJ/100 g) was carried out according to the provisions of Commission Regulation no. 1169/2011 (European Commission, 2011).

Total phenolic content was„ determined by Folin-Ciocalteu procedure, and antioxidant capacity by DPPH method (*Horszwald and Andlauer*, *2011* with some modifications (concerning extraction media, time and mode of extraction, extract volumes of the used sample and reagents, using UV-VIS Jasco V 550 spectrophotometer). Microbiological analysis was performed using the following methods: SR ISO 21527-1:2009 (Yeasts and molds), SR EN ISO 21528-1:2017 method (*Enterobacteriaceae*), SR ISO 6579-1:2017 method (*Salmonella*), SR EN ISO 6888-1:2021/A1:2023 (*Coagulase-positive Staphylococcus*), ISO 21807:2004 (Water activity). Water activity was determined using Aquaspector AQS 31 equipment.

RESULTS

Following the sensory analysis of the “Control Croissant,” the product was characterized by a pleasant, characteristic sweet taste and a specific aroma resulting from the harmonious balance between vanilla flavor and plum jam.

Following the sensory analysis of the product “Croissant fortified with grape pomace powder” (CSV_V1 and CSV_V2), the samples were characterized by a pleasant, characteristic sweet taste and a specific aroma resulting from the harmonious combination of vanilla flavor and plum jam with the functional ingredient (powder) obtained from the *Pinot Noir* variety.

Following the sensory analysis of the product “Croissant fortified with grape pomace powder,” corresponding to the experimental variant CSV_V3, the sample was found to exhibit a sour taste, attributed to the higher addition of the functional ingredient (powder) obtained from the *Pinot Noir* variety at a fortification level of 9%. Based on the results of the sensory analysis, the product “Croissant fortified with grape pomace powder” corresponding to the 6% fortification level (CSV_V2) was selected as the optimal variant for fortification.

Physico-chemical analysis showed that the product “Croissant fortified with grape pomace powder” (6% fortification level) had higher contents of total ash, lipids, total sugars, and crude fiber compared to the “Control Croissant.” Additionally, the product “Croissant fortified with grape pomace powder” (CSV_V2) exhibited lower protein and total carbohydrate contents compared to the control sample (Table 1).

Table 1

Physico-chemical indicators of the products "Control Croissant" (CSV_C) and "Croissant fortified with grape pomace powder" (CSV_V2)

Physico-chemical indicators	"Control Croissant" (CSV_C)	"Croissant fortified with grape pomace powder" (CSV_V2)
Moisture (%)	25.78±0.26	25.70±0.26
Ash (%)	0.86±0.01	0.97±0.01
Protein (%)	9.83±0.12	9.78±0.12
Lipids (%)	12.08±0.12	12.18±1.2
Carbohydrates (%)	51.45±0.46	51.37±0.46
Available carbohydrates (%)	49.17±0.44	48.33±0.44
Total sugar (%)	13.89±0.13	14.11±0.13
Crude fiber (%)	2.28±0.05	3.04±0.06
Energy value (kcal/100g)	349	348
Energy value (kJ/100g)	1468	1463

The protein content of the product "Croissant fortified with grape pomace powder" is comparable to that reported by *Catană et al. (2021)* for the product "Minicake fortified with *Aronia melanocarpa* pomace powder" (proteins = 10.35%). Additionally, the "Croissant fortified with grape pomace powder" exhibited a higher carbohydrate content compared to that reported by *Catană et al. (2024)* for the "Minicake fortified with cauliflower leaf powder" (carbohydrates = 43.67%), and a lower lipid content than that reported by *Antoniolli et al. (2024)* for the "Muffin fortified with grape pomace" (lipids = 20.33%).

The crude fiber content of the "Croissant fortified with grape pomace powder" was approximately 1.3 times higher than that reported by *Anwar et al. (2024)* for Cupcakes fortified with grape pomace powder at a 6% level (crude fiber = 2.28%). Moreover, the ash content of the fortified bakery product obtained in the present experimental study was comparable to that reported by *Anwar et al. (2024)* for "Cupcakes fortified with grape pomace" at the same fortification level (ash = 0.87%). The total sugar content was lower than that reported by *Catană et al. (2024)* for the product "Minicake fortified with cauliflower leaves powder" (total sugars = 33.60%) for variant V4 at a fortification level of 23%.

The total polyphenol content and antioxidant capacity of the products "Control Croissant" and " Croissant fortified with grape pomace powder" are presented in the Table 2.

Table 2

Total polyphenol content and antioxidant capacity of products "Control Croissant" (CSV_C) and "Croissant fortified with grape pomace powder" (CSV_V2)

Indicators	"Control Croissant" (CSV_C)	"Croissant fortified with grape pomace powder" (CSV_V2)
Total polyphenol content (mg GAE/100g)	187.75±4.69	317.48±7.94
Antioxidant capacity (mg TE/100g)	198.00±5.00	354.00±9.00

Due to the valuable ingredients used in the composition of the "Croissant fortified with grape pomace powder" the product stands out for its content in total polyphenols: 317.48 mg GAE/100g. The total polyphenol content of this croissant was approximately 1.7 times higher than that of the "Control Croissant." However, this value was lower than that reported by *Yalcin et al. (2022)* for whole wheat muffin cake fortified with 7.5% grape seed flour (total polyphenols = 421.10 mg GAE/100 g), but comparable to that reported by *Catană et al. (2021)* for the product "Minicake fortified with *Aronia melanocarpa* pomace powder" (396.86 mg GAE/100 g). Additionally, the product "Croissant fortified with grape pomace powder" exhibited a high antioxidant capacity (354.00 Trolox equivalents/100 g), which was approximately 1.8 times higher than that of the "Control Croissant." Moreover, this croissant showed an antioxidant capacity about 9.6 times higher than that reported by *Yalcin et al. (2022)* for whole wheat muffin cake fortified with 7.5% grape seed flour (37.02 Trolox equivalents/100 g).

The microbiological indicators of the products "Control Croissant" (CSV_C) and "Croissant fortified with grape pomace powder" (CSV_V2) are presented in Table 3.

Table 3

The microbiological indicators of the products "Control Croissant" (CSV_C) and "Croissant fortified with grape pomace powder" (CSV_V2)

Microbiological indicators	"Control Croissant" (CSV_C)	"Croissant fortified with grape pomace powder" (CSV_V2)
Yeast and mold (CFU/g)	< 10	< 10
Enterobacteriaceae (CFU/g)	< 10	< 10
Salmonella, in 25 g	Absent	Absent
Coagulase-positive Staphylococcus (CFU/g)	< 10	< 10
Water activity	0.848	0.842

Microbiological analysis indicated that both the “Control Croissant” (CSV_C) and the “Croissant fortified with grape pomace powder” (CSV_V2) complied with the requirements of the current legislation. Water activity values of 0.848 and 0.842 were recorded for CSV_C and CSV_V2, respectively.

CONCLUSIONS

The product “Croissant fortified with grape pomace powder” exhibits superior sensory qualities, high nutritional value, and significant antioxidant potential. Accordingly, this product is characterized by a high content of proteins (9.78%), total carbohydrates (51.37%), available carbohydrates (48.33%), and crude fiber (3.04%).

Due to the use of ingredients rich in polyphenols, the “Croissant fortified with grape pomace powder” stands out for its high total polyphenol content (317.48 mg GAE/100 g). Additionally, the product exhibits a high antioxidant capacity (354.00 mg TE/100 g).

From a microbiological perspective, the product “Croissant fortified with grape pomace powder” complies with the sanitary regulations in force.

The valorization of winemaking by-products through the development of functional ingredients (powders) intended for the fortification of bakery products is of considerable interest, as it contributes to environmental protection by reducing waste generation and enhances the added value of food products. Due to its complex biochemical composition, high polyphenol content, and significant antioxidant capacity, the “Croissant fortified with grape pomace powder” may be incorporated both into a healthy diet and into the diets of individuals affected by conditions associated with oxidative stress.

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EVALUATION OF THE AGROBIOLOGICAL PERFORMANCE OF FOREIGN WINTER WHEAT VARIETIES UNDER THE PEDOCLIMATIC CONDITIONS OF CENTRAL MOLDOVA

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EVALUAREA COMPORTAMENTULUI AGROBIOLOGIC AL UNOR SOIURI STRĂINE DE GRÂU DE TOAMNĂ ÎN RAPORT CU CONDIȚIILE PEDOCLIMATICE DIN REGIUNEA CENTRALĂ A MOLDOVEI

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Keywords: *environment, interaction, variety, winter wheat, yield.*

ABSTRACT

Understanding the interaction between winter wheat varieties and the growing environment helps identify traits associated with superior performance, as well as the conditions that allow an accurate assessment of their potential. In this context, at Agricultural Research and Development Station Secuieni, during the 2024–2025 growing season, the performance of 16 foreign wheat varieties was evaluated in terms of both yield and grain quality. Analysis of relative yield showed that all varieties exceeded the control (Katarina), confirming their productive potential and adaptability under the conditions of central Moldova. The results indicate that these genotypes can be successfully cultivated in farms aiming for high yields, with three varieties – Papillon, SU Mousqueton, and SU Correction – standing out with increases of approximately 21% compared to the control.

ABSTRACT

Înțelegerea interacțiunii dintre soiurile de grâu și mediul de cultură contribuie la identificarea trăsăturilor asociate performanțelor superioare, precum și a condițiilor care permit o evaluare corectă a potențialului acestora. În acest sens, la Stațiunea de Cercetare Dezvoltare Agricolă Secuieni, în anul agricol 2024–2025, a fost studiat comportamentul a 16 soiuri de grâu străine, atât din perspectiva productivității, cât și a calității boabelor. Analiza producției relative a evidențiat faptul că toate soiurile au depășit martorul (Katarina), confirmând potențialul lor productiv și adaptabilitatea în condițiile din centrul Moldovei. Rezultatele obținute au aratat că aceste genotipuri pot fi utilizate cu succes în ferme orientate spre obținerea unor producții ridicate, trei dintre ele – Papillon, SU Mousqueton și SU Correction, remarcându-se prin sporuri de aproximativ 21% față de martor.

INTRODUCTION

As well as being the most widely distributed food crop in the world, with more than 40% of the world's population relying on it as their staple food, wheat also plays an important role in food production and supply, providing about 20% of overall human energy consumption (*Dong, Q. et al., 2020; Umarov, I. et al., 2020*).

Straw cereals, especially wheat (*Triticum aestivum* L.), are the most widely cultivated plant in the world, grown in over 100 countries, and are a prime commercial source (Voinea and Ilie, 2023). Winter wheat is one of the most important crops in the world of particular economic importance, with bread made from wheat flour being the essential food, also ensuring about 20% of total calories consumed (*Chiriță, S. et al., 2023*). Wheat is an important source of energy and protein for humans all over the world. As wheat flours have the unique properties to form a strong and elastic dough, the majority of wheat is consumed in form of baked goods and a high baking quality is required (*Rossmann, A. et al., 2020*).

Wheat grains are rich in protein and gluten, and the breeding program is aimed at increasing the content in these indices (*Șerban, G. et al., 2022*). Wheat is an important source of energy and protein for

humans all over the world. As wheat flours have the unique properties to form a strong and elastic dough, the majority of wheat is consumed in form of baked goods and a high baking quality is required (*Rossmann, A. et al., 2020*).

Climate change has a major impact on agricultural growth and yields, with sudden temperature changes, a lack or abundance of precipitation, and CO_2 concentration directly influencing plant life cycles (*Tăbărașu, A. M. et al., 2023*). If there are no periods of low temperatures and frost, and if temperatures and precipitation patterns change, certain crops could benefit, while others, such as winter wheat, could suffer. Winter wheat requires cool conditions during the early stages of growth to complete vernalization and trigger reproductive development (*Zhao, C. et al., 2016*). Since the increase in temperature during winter and spring is significant in our country, the impact on winter wheat productivity has been negative. Additionally, current literature provides some evidence that the development of deep roots in winter wheat can lead to the loss of mineral nitrogen in the fall through leaching below the root depth.

Breeding research for the common wheat crop has focused on quality and yield. These are closely related to each other because high yield without adequate quality or good quality without satisfactory production are not profitable for the farmer (*Pintilie et al., 2023*).

MATERIALS AND METHODS

The research was carried out in the agricultural year 2024-2025, at A.R.D.S. Secuieni (Agricultural Research and Development Station Secuieni), a unit located in the north-western part of the Central Moldavian Plateau, and its objective was to assess the adaptability of sixteen winter wheat varieties.

The field experiment was placed on a typical cambic chernozem soil type, middle texture, acid: pHH_2O – 5.98, characterized as: supplied in phosphorus (77.6 ppm PAL), Ca (13.6 mEq/100 g soil Ca) and Mg (1.8 mEq/100 g soil Mg), middle supplied in active humus (1.88%) and nitrogen (16.2 ppm $N\text{-}NO_3$) and poorly supplied in potassium (124.6 ppm K_2O) (*Pochișcanu, S. et al., 2017*). The experiment was arranged using the latin rectangle method, with three replications, each winter wheat variety occupying a total area of 10 m². This method allowed for a rigorous evaluation of the differences between varieties, ensuring effective control of environmental variability. The obtained data were processed and statistically interpreted using the analysis of variance method (*Leonte and Simioniuc, 2018*).

Analysis of the thermal regime over the period from sowing to harvest reveals a year marked by significant temperature anomalies, with an increase of 1.4 °C relative to multiannual averages. This elevated thermal condition reflects a warmer than normal climate, with direct consequences for crop growth dynamics and the timing of phenological stages.

During the autumn period, temperatures were slightly above the multiannual average, favoring germination and crop establishment. This early warming contributed to uniform emergence and the accumulation of an adequate vegetative start. Winter, however, was marked by an alternation of warmer months and months slightly cooler than the multiannual average. Spring was generally warmer than usual, with above-average thermal input in March and April, nevertheless, May experienced temperatures below the multiannual mean. Summer was characterized by high temperatures exceeding the multiannual averages, particularly in June and July. Overall, the analyzed thermal regime reflects a clear warming trend, with significant effects on crop dynamics, water consumption, and plant phenology (Fig. 1).

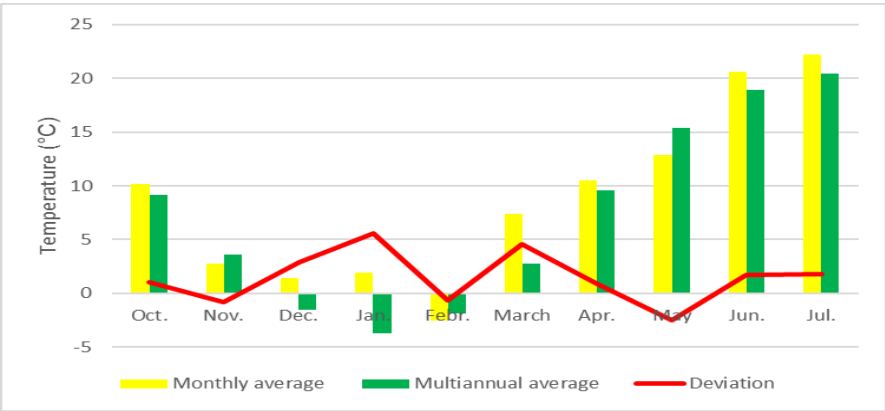

Fig. 1 – Temperature (°C) during the winter wheat vegetation period, A.R.D.S. Secuieni, 2024-2025

From a pluviometric perspective, the period from sowing to harvest exhibited pronounced variability and a general trend toward drought, confirmed by a total deficit of 76.7 mm compared to the multiannual average. This strong fluctuation between extremely dry and extremely wet months indicates pronounced climatic instability, increasingly characteristic of agricultural years affected by climate change. In the early part of the season, autumn and early winter months recorded values below the multiannual average, with the exception of December, potentially limiting the replenishment of soil water reserves following the warm period. Spring was marked by strong contrasts, March recorded above-average precipitation, while April experienced a severe deficit, however, May was atypically wet, temporarily contributing to the recovery of water reserves. June saw an extremely high pluviometric deficit of 76.2 mm, whereas July precipitation was much closer to multiannual averages (Fig. 2).

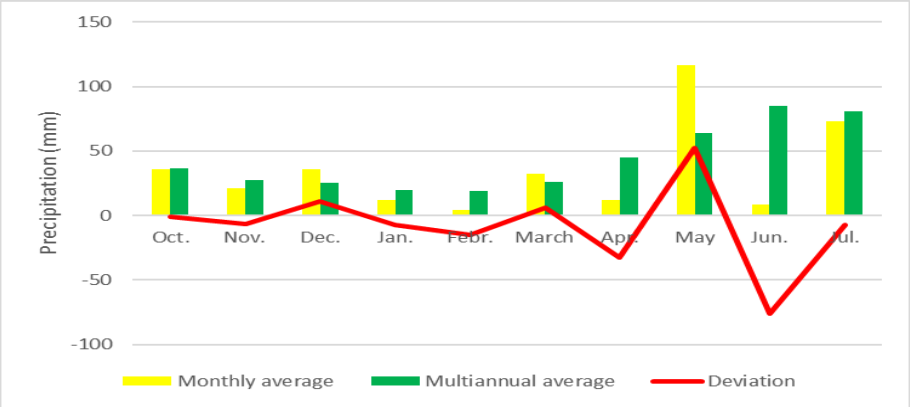

Fig. 2 – Precipitation (mm) during the winter wheat vegetation period, A.R.D.S. Secuieni, 2024-2025

RESULTS

The results presented in this paper come from research conducted in a comparative crop trial, in which different foreign winter wheat varieties were evaluated with the aim of highlighting their performance under the pedoclimatic conditions specific to the central area of Moldova.

Most varieties headed between May 20 and May 31, with some variation depending on the cultivar. The varieties Katarina and Avenue headed around May 20–21, while SU PULSION headed on May 31. This indicates that there are significant differences between varieties regarding the onset of the heading stage. Flowering occurred between June 2 and June 10, with most varieties flowering at the beginning of June (June 2–6). The varieties SU HORIZON and Karabol flowered later, on June 10 (Fig. 3).

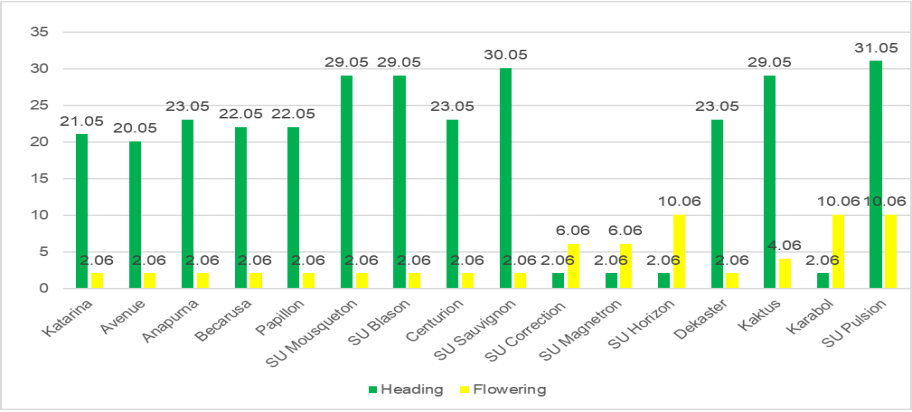

Fig. 3 – Winter wheat development stages: heading and flowering

Regarding plant height in the analyzed winter wheat varieties, the greatest height was recorded for the Centurion variety (98.6 cm), while the smallest was observed in the Becarusa variety (69.4 cm). Among the 16 studied varieties, five exceeded 90 cm in height, Centurion, SU Correction, SU Magnetron, SU Horizon, and Karabol (Fig. 4).

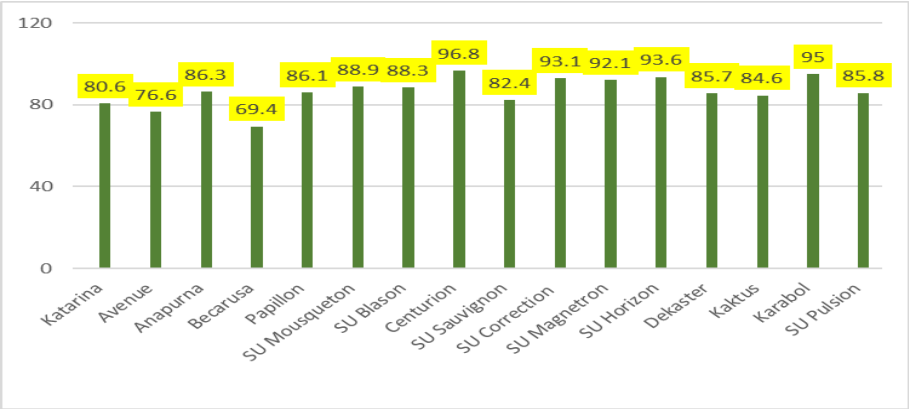

Fig. 4 - Plant height (cm) of the winter wheat varieties studied at A.R.D.S. Secuieni

Regarding the thousand-kernel weight, the highest value was recorded for the Centurion variety (59.3 g), indicating significantly larger grains compared to the other cultivars, while SU Blason had the lowest value (35.9 g). The highest hectoliter weight values were recorded for the Katarina (80.2 kg/hl) and Apapurna (79.4 kg/hl) varieties, whereas Kaktus exhibited the lowest value (75.1 kg/hl) (Fig. 5).

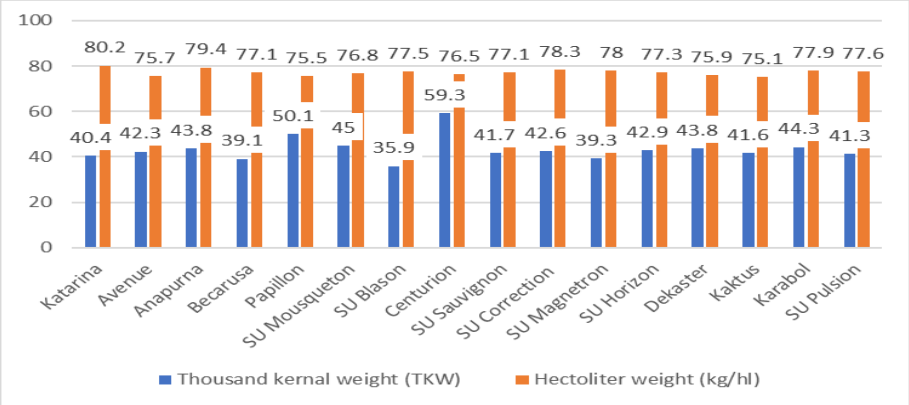

Fig. 5 - The thousand kernal weight (TKW) and hectoliter weight (kg/hl) at winter wheat varieties

The lowest winter wheat yield was obtained from the Katarina variety (10.896 kg·ha^{-1}), while the highest yield was recorded for the Karabol variety (13.370 kg·ha^{-1}). Out of the 16 varieties included in the study, eight of them (Anapurna, Papillon, SU Moisqueton, SU Blason, SU Sauvignon, SU Correction, SU Horizon, Kaktus) achieved higher yields than the control (Katarina), these results being statistically supported and interpreted as significant.

When evaluating relative yield performance, the results clearly indicate that all analyzed wheat varieties exceeded the yield of the control variety (Katarina), confirming a high productive potential. This positive trend highlights the superior genetic capacity of the tested cultivars and suggests that they may represent advantageous choices for farmers aiming to increase agricultural output. Among the varieties that stood out with the best results were Papillon, SU Mousqueton, and SU Correction, each showing relative increases of 21% compared to the control. These values reflect their ability to generate higher yields and indicate considerable agronomic potential for use in intensive cropping systems (Table 1).

Table 1

Yield recorded for winter wheat varieties under pedoclimatic conditions from A.R.D.S. Secuieni

Variety	Yield (kg · ha^{-1})	Relative yield (%)	Difference (kg · ha^{-1})	Signif.
Katarina	10.896	100	Ct.	-
Avenue	11.502	106	606	
Anapurna	13.020	119	2.124	*
Becarusa	11.418	105	522	
Papillon	13.080	120	2.184	*
SU Mousqueton	13.175	121	2.279	*

SU Blason	12.973	119	2.077	*
Centurion	12.378	114	1.482	
SU Sauvignon	12.777	117	1.881	*
SU Correction	13.174	121	2.278	*
SU Magnetron	12.123	111	1.227	
SU Horizon	12.706	117	1.810	
Dekaster	11.185	103	289	
Kaktus	12.806	118	1.910	*
Karabol	13.370	123	2.474	*
SU Pulsion	12.524	115	1.628	
LSD 5%	1.863			
LSD 1%	2.512			
LSD 0,1%	3.334			

The analyzed winter wheat varieties showed a protein content ranging between 9.7% and 13.3%, while gluten levels varied between 18.4% and 26.7%. A direct correlation was observed between protein and gluten content, with varieties high in protein generally also presenting higher gluten values.

Among all varieties, SU Magnetron stood out with the highest protein (13.3%) and gluten content (26.7%), followed by SU Correction (13.1%) and Dekaster (12.7%), making them suitable for high-quality breadmaking. Close to these values were Becarusa (12.5%) and Katarina (12.4%), also presenting good baking quality. At the opposite end were Kaktus (9.7%), Karabol (10.3%), SU Pulsion (10.1%), and SU Sauvignon (10.1%), which recorded the lowest protein and gluten contents (Fig. 6).

Winter wheat varieties with high gluten levels, such as SU Magnetron, SU Correction, Dekaster, Becarusa, and Katarina, can be successfully used in breadmaking, especially where good loaf volume and well-aerated crumb are desired. The varieties with the lowest gluten content were Kaktus (18.4%), Karabol (19.9%), SU Pulsion (19.3%), and SU Sauvignon (19.5%).

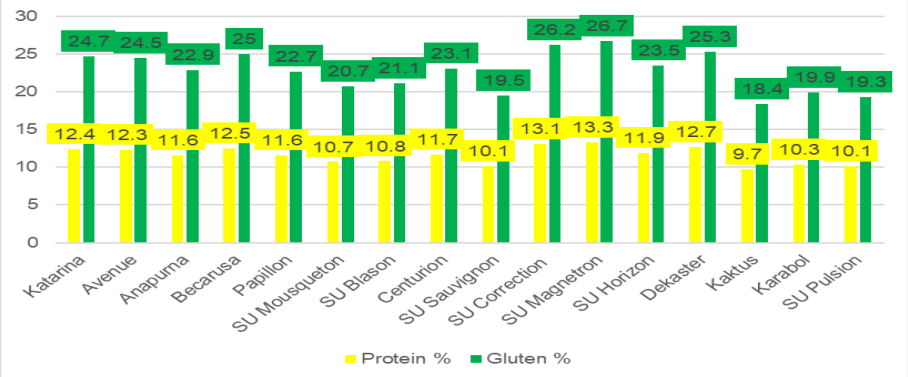

Fig. 6 - Protein (%) and gluten (%) content values at the studied genotypes

CONCLUSIONS

Research results revealed a clear differentiation in productivity among the winter wheat varieties, with yields ranging from 10.896 kg·ha-1 (Katarina) to 13.370 kg·ha-1 (Karabol). Most tested varieties exceeded the control, with eight of them showing statistically significant increases. Relative yield values indicated that all variants outperformed the control, with Papillon, SU Mousqueton, and SU Correction standing out by achieving yield increases of approximately 21%. These findings confirm the genetic value of the analyzed varieties and support their use in agricultural systems aimed at maximizing production.

The compositional analysis of protein and gluten in the 16 studied winter wheat varieties highlights significant variability among genotypes, with protein content values ranging from 9.7% to 13.3%, and gluten content ranging from 18.4% to 26.7%. Among them, SU Magnetron, SU Correction, and Dekaster recorded the highest values for both parameters, recommending them for high-quality breadmaking, while Kaktus, Karabol, SU Pulsion, and SU Sauvignon presented lower levels.

Overall, the analysis of the evaluated winter wheat varieties demonstrated considerable variability in both technological quality, determined by protein and gluten content, and productive potential. However, for a more reliable and reproducible assessment of these results, multi-year testing under different environmental and cultivation conditions is required to confirm the stability of the analyzed traits.

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TYPES AND CHARACTERISTICS OF SOIL SAMPLING TERMINALS
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TIPURI ȘI CARACTERISTICI ALE TERMINALELOR DE PRELEVARE A PROBELOR DE SOL

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Keywords: *soil sampling, sampling mechanisms, soil penetration depth, automation level*

ABSTRACT
Soil sampling represents a critical stage in analyzing the composition and quality of land for agricultural, geotechnical, and environmental applications. The performance of this process is significantly influenced by the terminals used, such as augers and sampling probes. These components must ensure efficient soil penetration while maintaining sample integrity and minimizing contamination or alteration of the natural stratification. This article analyzes various types of sampling terminals, highlighting the materials used, specific geometries, and modern manufacturing technologies. It discusses the influence of design parameters on collection efficiency, including factors such as wear resistance, penetration capacity in compact soils, and sample retention ability. Conventional solutions are also compared with advanced ones, such as augers with special treatments for increased durability or heads equipped with automatic sample-sealing mechanisms. The study provides a detailed perspective on the most efficient terminal configurations, emphasizing their advantages and limitations depending on the type of soil analyzed. The conclusions underline the importance of selecting optimized sampling heads for specific usage conditions, thereby contributing to improved soil analysis accuracy and the optimization of sampling processes.

REZUMAT
Prelevarea probelor de sol reprezintă o etapă critică în analizarea compoziției și calității terenurilor pentru aplicații agricole, geotehnice și de mediu. Performanța acestui proces este influențată semnificativ de terminalele utilizate, cum ar fi burghiele și sondele de prelevare. Aceste componente trebuie să asigure o penetrare eficientă în sol, menținând în același timp integritatea probei și reducând la minimum contaminarea sau alterarea stratificației naturale. În acest articol, sunt analizate diferite tipuri de terminale de prelevare, evidențiindu-se materialele utilizate, geometriile specifice și tehnologiile moderne de fabricație. Se discută influența parametrilor de proiectare asupra eficienței de colectare, inclusiv factori precum rezistența la uzură, capacitatea de pătrundere în soluri compacte și capacitatea de reținere a probei. De asemenea, sunt comparate soluțiile convenționale cu cele avansate, precum burghiele cu tratamente speciale pentru durabilitate sporită sau capetele prevăzute cu mecanisme automate de sigilare a probei. Studiul oferă o perspectivă detaliată asupra celor mai eficiente configurații de terminale, evidențiind avantajele și limitările acestora în funcție de tipul de sol analizat. Concluziile subliniază importanța alegerii unor capete de prelevare optimizate pentru condițiile specifice de utilizare, contribuind astfel la îmbunătățirea preciziei analizelor solului și la optimizarea proceselor de prelevare.

INTRODUCTION
Soil sampling represents a fundamental operation in agricultural engineering, environmental monitoring, geotechnical investigations, and land management, as the accuracy of soil analyses largely depends on the quality and representativeness of the collected samples *(De Cauwer, V. et al., 2025)*.Soil sampling terminals, also referred to as soil sampling devices or systems, are designed to extract soil material from different depths and under varying field conditions, ensuring minimal disturbance of the soil structure while preserving its physical and chemical properties. The diversity of soil types, land uses, and analytical objectives has led to the development of a wide range of soil sampling terminals, each optimized for specific applications and operational requirements *(Nguyen et al, 2024)*.

The increasing demand for precise soil characterization, driven by precision agriculture, sustainable land use practices, and environmental regulations, has further highlighted the importance of selecting appropriate soil sampling terminals *(Nguyen et al, 2024)*. Factors such as sampling depth, soil texture, moisture content, compaction level, and the intended laboratory analyses all influence the choice of sampling equipment. Consequently, understanding the types and characteristics of soil sampling terminals is essential for researchers, engineers, and practitioners involved in soil assessment and monitoring activities *(De Cauwer, V. et al., 2025)*.

Soil sampling terminals can be broadly classified according to several criteria, including their operating principle, domain of use, sampling depth, and degree of automation. From a functional point of view, these

devices are commonly divided into terminals designed for surface soil sampling and those intended for deep soil sampling. Surface sampling typically targets the topsoil layer, which is most affected by agricultural practices and environmental interactions, while deep sampling focuses on subsurface layers relevant to root development, groundwater protection, geotechnical stability, or contamination assessment *(Schmidinger, J., et al., 2024)*.

One of the most important distinguishing characteristics among soil sampling terminals is the mechanism used for soil penetration and sample collection. Mechanical penetration methods include manual force, rotational drilling, percussion, or hydraulic actuation, each offering specific advantages and limitations. Rotational systems, such as augers, are widely used due to their simplicity, adaptability to different soil textures, and cost-effectiveness *(Schmidinger, J. et al., 2024)*. Percussion-based systems, on the other hand, are better suited for compacted or cohesive soils, where penetration resistance is high. Hydraulic and motorized systems are increasingly employed in automated or semi-automated terminals, allowing greater control over sampling depth, force, and consistency.

Another key aspect in the classification of soil sampling terminals is the level of sample disturbance. Some applications, such as chemical analysis of nutrients or contaminants, allow for disturbed samples, where the soil structure is not preserved. In contrast, geotechnical and physical analyses often require undisturbed samples to accurately determine properties such as bulk density, porosity, shear strength, or permeability. This requirement has led to the development of specialized sampling terminals, such as piston samplers and split-spoon samplers, which are designed to minimize structural alteration during extraction *(Pham, T.-H. et. al., 2024)*.

The domain of use also plays a significant role in defining the characteristics of soil sampling terminals. In agriculture and environmental monitoring, portability, ease of use, and rapid sampling are often prioritized, especially when large areas must be covered. Conversely, in geotechnical engineering and scientific research, sampling accuracy, depth capability, and sample integrity are of greater importance, even if this implies more complex and heavier equipment. Additionally, recent advancements in automation and robotics have enabled the integration of soil sampling terminals into autonomous platforms, such as ground vehicles or aerial systems, further expanding their applicability.

The degree of automation represents a modern and increasingly relevant classification criterion. Traditional soil sampling terminals are predominantly manual, requiring direct human operation and physical effort. Semi-automated systems incorporate mechanical or hydraulic assistance to reduce operator workload and improve repeatability. *(Schmidinger, J. et al., 2024)*. Fully automated soil sampling terminals, often integrated with sensors, control systems, and data acquisition units, enable consistent sampling procedures, reduced human error, and compatibility with precision agriculture and smart monitoring systems. These systems are particularly valuable in applications requiring frequent or large-scale soil sampling campaigns.

In addition to functional and operational characteristics, soil sampling terminals are also defined by construction materials, durability, maintenance requirements, and adaptability to different soil conditions. Materials must withstand abrasive soils, moisture, and corrosion, while ensuring ease of cleaning to prevent cross-contamination between samples *(De Cauwer, V. et al., 2025)*. Modular designs and interchangeable sampling heads further enhance versatility, allowing a single terminal to be used across multiple applications and soil types.

In conclusion, soil sampling terminals represent a critical interface between the soil environment and analytical processes. Their types and characteristics directly influence the reliability of soil data and consequently, the decisions based on that data. A comprehensive understanding of the available soil sampling terminals, their operating principles, and their specific features is essential for selecting the most suitable equipment for a given application. This chapter provides the foundation for a detailed analysis of the main types of soil sampling terminals and their defining characteristics, serving as a basis for informed selection and effective use in both traditional and automated soil sampling systems *(Pham, T.-H. et. al., 2024)*.

Determining soil quality – Soil analyses allow the evaluation of pH, nutrient content (nitrogen, phosphorus, potassium, etc.), organic matter, and other chemical and physical characteristics of the soil. Identifying soil problems – Soil samples can reveal issues such as soil compaction, salinity, contamination with heavy metals, or other toxic substances. Land use planning – Knowledge of soil characteristics helps in selecting the most suitable crops or land uses, thereby optimizing productivity and sustainability in agricultural and forested lands. Soil sampling devices can be classified according to their operating principle, field of application, and degree of automation. From a functional perspective, they are divided into devices intended for sampling from the surface layer or from deeper soil layers, differentiated by the type of penetration mechanism and sample collection method *(Yang, L., et al., 2025)*.

Fig. 1 – Collection of a soil sample

The main categories are:

- Soil sampling probes (augers, bucket-type, for sandy soils, clayey soils, etc.)
- Sampling tubes
- Split-spoon samplers
- Piston samplers

MATERIALS AND METHODS

Types of Soil Sampling Terminals and Construction Characteristics

The sampling scoop can be used for collecting surface soil samples. It can also be employed for soil homogenization or for collecting various types of solid materials. Scoops made of stainless steel are the most recommended; however, models manufactured from other materials may be suitable in certain situations, such as polyethylene scoops, which are used for sediment sampling intended for trace element analysis *(Di Vito, D., et al., 2025).*

The bucket-type auger consists of a cylindrical stainless-steel body, equipped at the lower end with sharp spiral blades and at the upper end with a coupling structure that allows the attachment of an extension rod and a T-shaped handle. During operation, the tool is rotated clockwise using the handle, progressively advancing into the soil as it cuts and loosens the material, which is then lifted and retained inside the cylindrical body. The cutting diameter varies depending on the auger model. The total length of a standard auger is approximately 30 cm, while extension rods allow sampling at depths of several meters.

The soil coring terminal consists of a mechanically machined split cylinder made of stainless steel, provided at both ends with threaded connections for assembly, a cutting tip, and an end cap, as well as a sliding hammer used to drive the assembly into the soil. Both the cutting tip and the end caps are manufactured from stainless steel to ensure mechanical strength and to prevent sample contamination *(Yang, L., et al., 2025).* The use of a plastic liner and a soil retention basket is optional, depending on the sampling conditions.

The split-spoon sampling terminal is used for collecting soil samples from depth. This device consists of a longitudinally split steel pipe section, made of carbon steel or stainless steel, fitted at one end with a penetration tip (drive shoe) and at the other end with an impact head (drive head).

Such devices are available in a variety of lengths and diameters, depending on drilling conditions and sampling objectives. Typically, they are driven into the soil by percussion, using repeated blows from a hammer weighing approximately 63.5 kg, dropped from a height of about 76 cm, mounted on the drilling rig *(Di Vito, D., et al., 2025)*. A piston sampler is principally a thin-wall tube sampler with a piston, street, and a changed sampler head. It's used to gather undisturbed soil samples from comfortable soil the place the pattern restoration is incessantly tricky and every so often in stiff soils. The sampler is equipped with a piston positioned at the base of the sampling tube. It is carefully lowered into the borehole and, once it reaches the bottom, the piston rod is fixed relative to the borehole base. Hydraulic or mechanical force is then applied to gradually advance the thin-walled tube into the soil, without the use of impact or driving forces.

After sampling, the device is withdrawn from the borehole and the vacuum between the piston and the sample is released. Disturbed samples are then collected from the top and bottom of the core for identification purposes. This system produces high-quality samples with a high probability of successful recovery. The fixed piston prevents premature soil entry at the start of sampling, ensuring recovery ratios do not exceed 100%. It also maintains a constant rate of soil entry throughout tube advancement, thereby increasing the likelihood of full sample recovery.

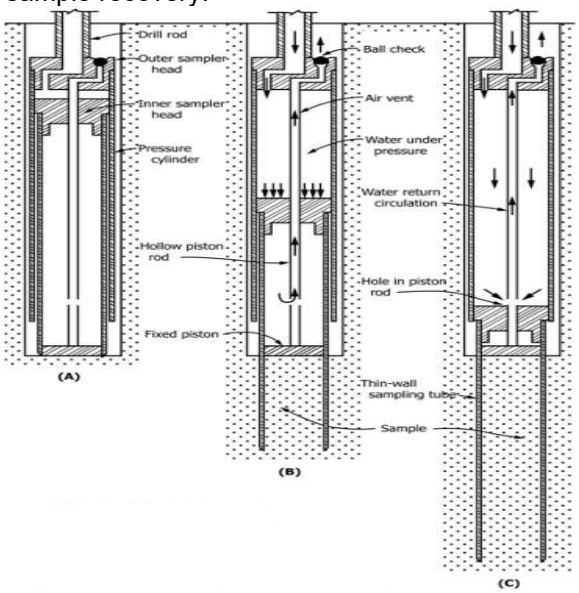

Fig. 2 - Fixed hydraulic piston sampler operation

The Dames and Moore (D&M) sampler is an advanced device primarily designed for collecting fine sands and silty soils. It features an Osterberg-type, hydraulically actuated fixed-piston mechanism capable of retrieving relatively “undisturbed” soil samples. The sampler uses a 50 cm long brass liner with a smooth interior, which effectively reduces friction between the soil and the tube walls.

A notable innovation of the D&M sampler lies in its sealing system. During insertion, a vacuum is generated that retains the soil sample within the liner, enabling the recovery of samples up to 45–50 cm in length and preventing soil from falling back into the borehole. This vacuum is maintained by a neoprene skirt seal positioned at the junction of the pressure cylinder and the liner. The seal not only blocks disturbed soil from entering the liner from the bottom of the borehole but also functions as a check valve for the driving pressure. Figure 3 presents a schematic of the D&M sampler components *(Cordeiro, D., et al., 2021).*

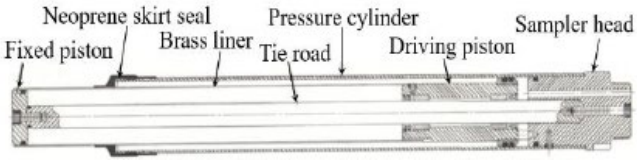

Fig. 3 - Schematic of D&M sampler components

The Gel-push (GP) sampler is an advanced soil sampling device developed by Kiso-Jiban Consultants to recover high-quality, undisturbed samples of granular soils. It uses a triple core barrel and a viscous polymer gel as drilling fluid, which lubricates the sample, reduces friction during sampling and extrusion, and helps preserve soil structure—an important aspect for liquefaction assessment. The GP-Static version combines fixed-piston sampling principles with polymer gel drilling. Unlike conventional samplers, the GP-S features a cutting shoe and three pistons: a stationary piston, an advancing piston that contains and injects gel, and a core-catcher activating piston. The system collects the soil sample in a 1 m long metallic liner.

The GP-S sampling process consists of three phases: (1) assembling the sampler, preparing a 1% polymer gel, and drilling a 150 mm borehole; (2) lowering the sampler, pumping water at constant pressure or penetration rate to advance the core barrel while gel lubricates the sample; and (3) advancing to full liner depth, allowing gel flow to facilitate sample movement and closing the core catcher to retain the soil.

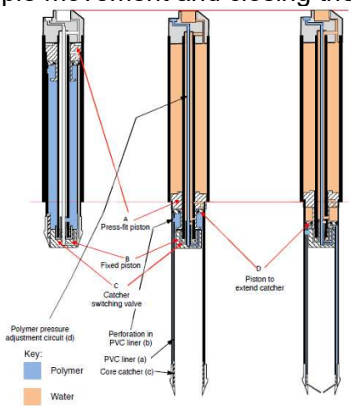

Fig. 4 - GP-S operation

The Shelby tube is primarily used to obtain geological information but can also be applied for collecting samples intended for chemical analyses.

Shelby tube samplers are thin-walled, hollow steel tubes, which are driven into the ground to extract a relatively undisturbed soil sample for use in laboratory tests used to determine density, permeability, compressibility and strength. Each tube has one end that is chamfered to form a cutting edge and the upper end includes holes for securing the tube to a drive head. Shelby tubes are useful for collecting soils that are particularly sensitive to sampling disturbance, including fine cohesive soils and clays. The tubes can also be used to transport samples back to the lab as well. Sampling is typically performed by pushing the Shelby tube steadily into the soil at a constant rate, without rotation, in order to minimize disturbance and alteration of the soil structure. Once the desired penetration depth is reached, the tube is carefully withdrawn, and the soil sample is sealed at both ends to preserve its natural moisture content and in-situ conditions during transport.

Despite their advantages, Shelby tube samplers present certain limitations. They are not well suited for coarse-grained soils, such as sands and gravels, where sample disturbance and loss are more likely to occur. Additionally, driving the tube into very stiff or cemented soils may cause deformation of the tube or excessive disturbance of the sample. For these reasons, their application is generally restricted to soft to medium-stiff cohesive soils.

Nevertheless, due to their simplicity, low cost, and ability to recover relatively undisturbed samples, Shelby tubes remain one of the most widely used sampling methods in geotechnical and environmental investigations, particularly when high-quality samples of fine-grained soils are required for laboratory tests.

Table 1

Comparative table between the main soil sampling devices

Sampling head type	Recommended soil	Disturbance level	Actuation method	Typical depth	Remarks
Classic augers	Sand, clay, silt, mixed soils	Medium – high	Manual / motorized rotation	0–0.5 m	Rapid, adaptable, disturbed samples;
Sampling tubes	Clay, cohesive and moist soils	Low – nearly intact	Manual / mechanical pushing	0,5–3 m	Undisturbed samples, for geotechnical and chemical analyses;
Sampling tubes	Mixed, clayey, sandy soils	High	Percussion (hammer-driven)	0,5–6 m	SPT standard, disturbed samples, used in geotechnical engineering;
Piston samplers	Clay, fine-grained, moist soils	Low – relatively intact	Manual / hydraulic piston	0,5–3 m	Samples preserve the natural structure, ideal for detailed analyses

Fig. 5 - Sampling scoop

Fig. 6 - bucket-type auger

Fig. 7 - Piston sampler

Fig. 8 - Split-spoon sampler

Fig. 9 - Shelby tube

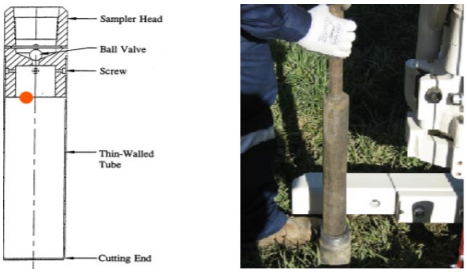

Fig. 10 - Thin-walled tube soil sampler: construction and practical use

RESULTS

In a study made by A. Viana et. al., the authors investigated the efficiency of two advanced soil sampler heads – Dames & Moore (D&M) and Gel-Push Static (GP-S) – for collecting high-quality samples from liquefiable sandy soils, where obtaining undisturbed samples is typically difficult. The study was conducted at a pilot site in Benavente, Portugal, an area with a history of seismic liquefaction.

The experimental campaign included site investigation using SCPTu to identify the sandy strata, sampling of 29 specimens (17 GP-S and 12 D&M) at depths between 5–12 m, controlled transportation and handling of the samples to minimize disturbance. Evaluation of sample quality by comparing the shear wave velocity (Vs) measured in situ (SCPTu) and in the laboratory (bender element tests).

Both sampler heads (D&M and GP-S) demonstrated a high capability to collect samples with low disturbance in silts and silty sands. Over 90% of the samples were classified as excellent or very good quality, based on the normalized Vs ratio.

The reduced friction at the soil-tube interface (via brass tubes for D&M and polymeric gel for GP-S) led to minimal soil compression during sampling. Sample recovery was good, although medium clean sands posed difficulties for both systems (sample loss upon extraction). The comparison of Vs in situ – laboratory proved to be an effective method for sample quality assessment, provided appropriate normalization based on state and effective stress was performed.

The authors demonstrated that modern sampler heads (D&M and GP-S) represent a significant advance in the study of liquefiable soils, allowing for the acquisition of representative samples with well-preserved structure and fabric, suitable for advanced geotechnical testing. The study also underscores the importance of proper transportation, handling, and storage to maintain sample quality. *(Viana da Fonseca, A., et al., 2019).*

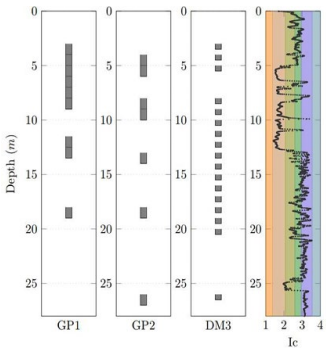

Fig. 11 - Samples collected by GP-S and D&M, and Ic from CPTu data

CONCLUSIONS

The design and operating principle of the sampling terminal directly affect the degree of soil disturbance, recovery ratio, and representativeness of the collected sample. Parameters such as wall thickness, cutting geometry, penetration method, and friction control are decisive in preserving the natural structure and in situ properties of the soil.

Each sampling head type—rotary augers, split-spoon samplers, thin-walled tubes, piston samplers, or advanced low-friction devices—is suited to specific soil conditions and investigation objectives. Disturbed sampling tools are efficient and robust for classification purposes, while undisturbed samplers are essential for advanced geotechnical and mechanical analyses. Soil disturbance during sampling is primarily governed by friction along the sampler walls, stress redistribution at the cutting edge, and the mode of penetration. Rotary and percussive terminals tend to induce higher disturbance due to shear and vibration, whereas push-in and piston-based systems reduce soil remolding by controlling penetration forces and soil entry rates.

Rotary and auger-based sampling heads are effective for rapid penetration, shallow investigations, and automated or robotic systems; however, they typically produce disturbed samples. Their primary value lies in stratigraphic identification, preliminary assessment, and integration into autonomous or continuous sampling platforms. At greater depths, mechanical robustness and controlled penetration become increasingly important, influencing the choice of terminal geometry and actuation method.

ACKNOWLEDGEMENT

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STUDIES AND RESEARCH ON IMPROVING THE PERFORMANCE OF A RECIRCULATING AQUACULTURE SYSTEM BY ADOPTING INNOVATIVE TECHNICAL SOLUTIONS

/

STUDII ȘI CERCETĂRI ASUPRA ÎMBUNĂTĂȚIRII PERFORMANȚELOR UNUI SISTEM ACVACOL RECIRCULANT PRIN ADOPTAREA UNOR SOLUȚII TEHNICE INOVATIVE

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Keywords: *RAS, radial flow settler, mechanical filters*

ABSTRACT

This paper aims to present a way for technical solutions implemented within a RAS, to reach a maximum of production and also obtain to a better control of processes taking place in the system.

The main way of achieving these objectives is to upgrade an existing facility by integrating equipment which will help improve the living conditions in the pools and hence the welfare of fish.

One of the first objectives of this paper is to present the changes that have been made by redesigning an old recirculating system (inefficient) into an efficient system capable of ensuring an optimum level of growth and development of the fishing material in the ponds.

The next objective of the work is related to the importance accorded to the use of hydraulic calculations for correct sizing of the pipes for a RAS.

ABSTRACT

Această lucrare își propune să prezinte o modalitate prin care soluțiile tehnice implementate în cadrul unui SAR (Sistem de Recirculare a Peștilor) permit atingerea unui nivel maxim de producție și, de asemenea, obținerea unui control mai bun al proceselor care au loc în sistem. Principala modalitate de atingere a acestor obiective este modernizarea unei instalații existente prin integrarea de echipamente care vor contribui la îmbunătățirea condițiilor de viață din bazine și, implicit, a bunăstării peștilor. Unul dintre primele obiective ale acestei lucrări este de a prezenta modificările aduse prin reproiectarea unui sistem de recirculare vechi (ineficient) într-un sistem eficient, capabil să asigure un nivel optim de creștere și dezvoltare a materialului piscicol din bazine. Următorul obiectiv al lucrării este legat de importanța acordată utilizării calculelor hidraulice pentru dimensionarea corectă a conductelor pentru un SAR.

INTRODUCTION

To promote a competitive aquaculture, at the highest sustainable standards it is necessary that a a recirculating system possess technologies and modern technical equipment that can deal with all the challenges that occur when the system is running (*Brinker and Rosch, 2005; Bordeasuet al., 2013*).

Waste from fish farms can cause a real environmental problem, therefore the concern for finding solutions to reduce and control them exists, bearing in mind that fish production in intensive and super intensive systems is a growing problem (*Stefanov C., 2014*).

A particular challenge in the process of redesigning the recirculating system was to find a optimal configuration that gives the possibility to install a radial flowing settler on the escape route the wastewater as shown in Figure 1 and Figure 2.

MATERIALS AND METHODS

To facilitate the preliminary removal of suspended solids from the water column, RAS frameworks frequently incorporate radial flow settlers alongside specialized pre-filtration units. Current research (*Willian and Shulin, 2006*) suggests that these technologies offer significantly higher efficiency levels compared to conventional sedimentation tanks. To maintain optimal water quality and system stability, it is imperative that the radial flow settler, as a core component of the wastewater treatment circuit, remains operational on a continuous 24-hour basis.

The operating principle of the radial flow settler for partial removing solid accumulations of water is simple as it can be seen in the flowchart shown in figure 3 (*Stefanov C., 2014*). The route of recirculated water is discharged from the growing tanks being directed through the central pipe 2, which discharges into a tube 3 positioned in the centre and opened at both ends, which is intended to reduce the turbulent flow of water that once has deposited solids on the bottom of the cone and now to prevent the return of suspension.

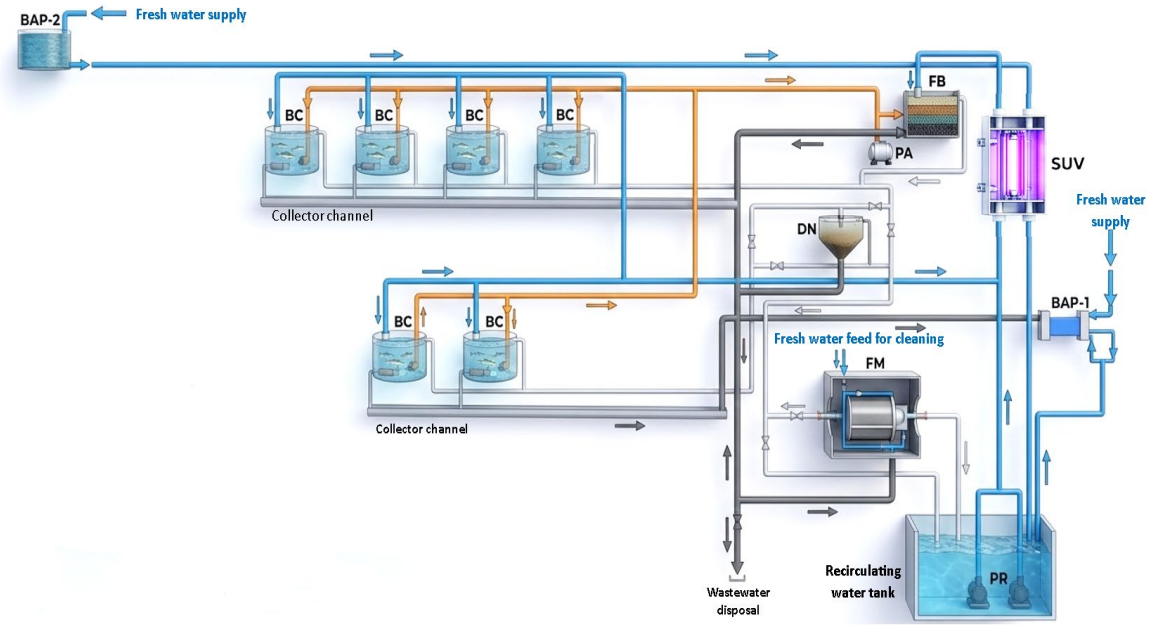

Fig.1 - Flowchart of RAS

BAP-1,2 - Fresh water tank; BC - Breeding tank; FB - Biological filter; PA - Air pump; SUV - UV sterilizer; DN - Sludge decanter; FM - Mechanical filter; PA - Recirculating pumps; PR - Recirculating pumps

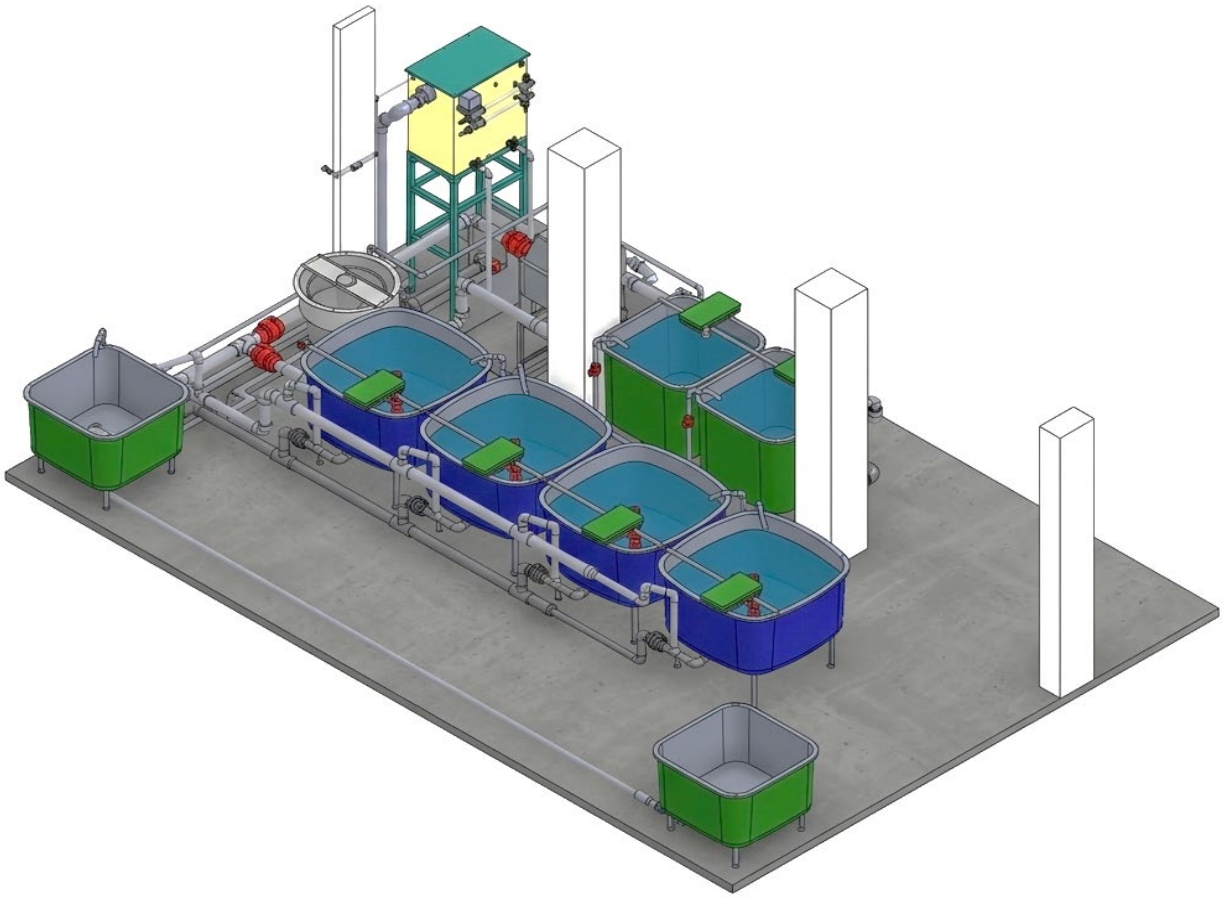

Fig.2 - 3D modelling of a recirculating system

According to the principle of communicating vessels water coming down through the central tube 3 enters the radial flow settler and is discharging in radial direction over a jagged wall in in the overflow 4, overflow that is surrounding sedimentation zone, and the filtered water is sent further to the mechanical filter (*Davidson and Summerfelt, 2005*).

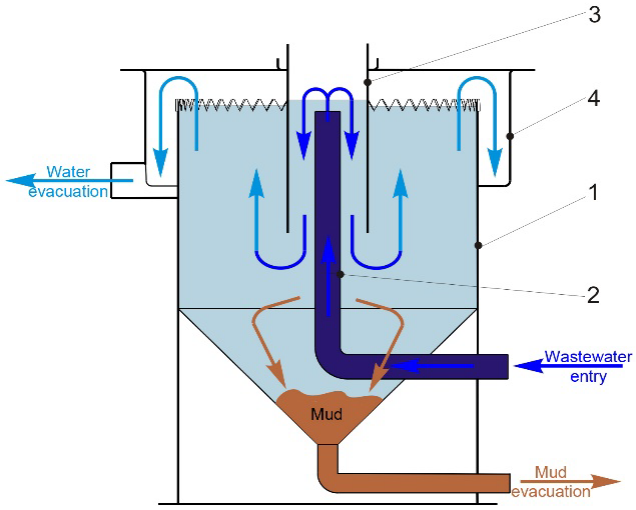

Fig. 3 - Technological operating scheme of radial flow settler [8]
1 - decanter; 2 - inlet tube, 3 - tube, 4 - overflow

One of the main issues that interest in the functioning of the radial flow settler is the speed of sedimentation of solids from the water sedimentation rate which is influenced by the differences between the section of the inlet tube 2 and the diameter of the body of the decanter 1, aspect that decreases significant the transfer speed which allows water to settle solids in the cone (*Davidson and Summerfelt, 2005*).

Removal of solid particles inside the decanter can only occur if sedimentation rate is higher than the ascending speed of water flow, Figure 4 (*Kocameni and Aktan, 2012*). Regarding the remove of solids that were decanted in conical crater, they will be periodically discharged through a collector pipe by opening a valve (*Davidson and Summerfelt, 2005*).

Solid particles that result from application in aquaculture are considered discrete particles whose sedimentation velocity V_s, is a value that is closely related to their size and weight specifications (*https://www.deq.idaho.gov/media/488801-aquaculture_guidelines.pdf*).

According to (William Johnson, Shulin Chen) the sedimentation velocity V_s can be determined theoretically for small solid particles with a low Raynolds number by applying the law of Stoke`s (*William and Shulin, 2006*).

$$V_S = \frac{g(\rho_s - \rho)d^2}{18\mu} \quad (1)$$

To determine the minimum speed of solid sedimentation, particles are using the relationship 2.

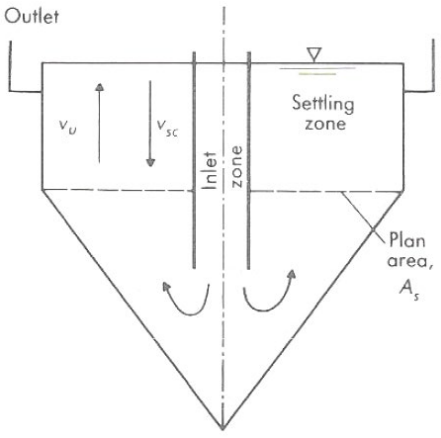

Fig.4 - Scheme of radial flow settler with representation of sedimentation rates and water drain from the unit [6]

$$V_S = \frac{Q}{A} \quad (2)$$

A particularly important step in designing a RAS is the sizing of inlet and exhaust pipes for the system. Regarding the installation for water supply in a recirculating system, the main requirement for optimal running of all machinery is to ensure sufficient pressure to lift water from the feed point to the consumer points in order to cover the loss in pipes and get the pressure and used flow (*Dumitrescu L.D., 1980*).

So, then the real fluid flow can occur in two different regimens relative to their physical structure: the laminar and the turbulent regime (*Brinker and Rosch, 2005; Bordeasuet al., 2013*). In figure 5 are the two types of flow shown: laminar and turbulent of real fluids (*http://www.scritub.com/tehnica-mecanica/BIOMECANICA-LICHIDELOR-HEMODIN42152.php*, *https://www.deq.idaho.gov/media/488801-aquaculture_guidelines.pdf*).

The difference between these two movements is in fact that laminar flow is a movement with uniform character, whereas turbulent flow is characterized by vortex and its moving character is uneven (*Florescu I, 2007*).

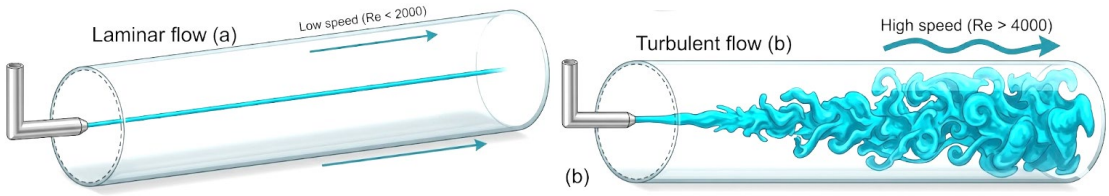

Fig. 5 - Fluid Flow (*http://www.scritub.com/tehnica-mecanica/BIOMECANICA-LICHIDELOR-HEMODIN42152.php*)
(a) laminar flow, (b) turbulent flow

According to Reynolds's theory two factors are influencing the flow regimes, laminar or turbulent; the flow of liquid through a pipe has: mean flow velocity *V*, the pipe diameter d and kinematic viscosity ν (*Bordeasu et al., 2013*).

$$\frac{\rho \cdot V \cdot d}{\eta} = \frac{V \cdot d}{\nu} = Re \quad (3)$$

$$\eta = \rho \cdot \nu \quad (4)$$

where ***Re*** - is called the criterion or Reynolds number.

Another essential component in the functioning of RAS is the drain installation for wastewater tanks, that just as the installation of water supply needs a correct sizing of its hydraulic. The main hydraulic condition through horizontal pipes is that real speed V_r must be higher or at least equal to the minimum speed of self-cleaning V_{min} and less than or at most equal to the maximum speed Vmax through these pipes (*http://www.scritub.com/stiinta/arhitectura-constructii/Proiectarea-instalatiilor-inte74922922.php*).

$$V_{min} \leq V_r \leq V_{max} \quad (5)$$

In case of the evacuation systems of wastewater the allowed minimum speed in horizontal closed pipes is 0.7 m/s and 0.5 m/s in opened. And the maximum speed for horizontal pipes must not exceed 4 m/s speed that depends on the type of material from which the pipe is made (*http://www.scritub.com/stiinta/arhitectura-constructii/Proiectarea-instalatiilor-inte74922922.php*).

RESULTS

Following the redesign process and the hydraulic simulations conducted for the Recirculating Aquaculture System (RAS) dedicated to pikeperch farming, several fundamental results have been obtained.

A hydraulic efficiency and flow regime control by analysing of the fluid flow regime through the supply pipes revealed a controlled transition between laminar and turbulent flow. Using the Reynolds number (Re) as a performance indicator allowed for precise diameter calibration to avoid excessive head losses. It was observed that a slightly turbulent flow at the tank inlets promotes optimal mixing of dissolved oxygen, eliminating "dead zones" where water quality could otherwise degrade and impact fish health.

Hydraulic calculation check for the actual real speed V_r, is performed by knowing the flow rate Q_c of the drum assembly u and the slope of the pipe. The degree of filling u represents an essential parameter in the calculations of hydraulic exhaust pipes for wastewater and is determined as the ratio between the height h of water status and pipeline diameter d of pipeline section, figure 6 (http://www.scritub.com/stiinta/arhitectura-constructii/Proiectarea-instalatiilor-inte74922922.php).

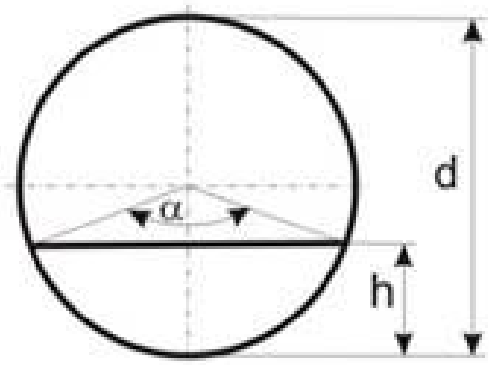

Fig. 6 - The degree of filling for the discharge pipe

Another result is the performance of the radial flow decanter, so the integration of the radial flow settler proved to be a turning point in organic load management. Experimental data show that by maintaining a water rise velocity V_u lower than the particle sedimentation velocity V_s, the system achieved a capture rate of over 80% for coarse solids before they reached the fine mechanical filtration stage. This significantly reduced the backwashing frequency of the drum filter, lowering fresh water and energy consumption.

Table 1

The filling degree (s) depending on the nature of the wastewater and the diameter of the pipe

Nature wastewater	The nominal diameter of the pipe, *dn*, [mm]			
	≤ 100	125	150 - 200	> 200
	u			
Domestic and industrial wastewater, suspensions greater than 5 mm	0.65	0.65	0.65	0.65
Stormwater and industrial wastewater conventional clean	1.00	1.00	1.00	1.00
Industrial wastewater with suspension lower than 5 mm	0.70	0.70	0.80	0.80

The validation of self-cleaning capacity vas done by sizing of the discharge pipes was confirmed by calculating the filling degree and the hydraulic slope. The results demonstrate that the real flow velocity *Vr* exceeds the critical threshold of 0.7 m/s, thus ensuring the constant transport of sediments toward the filtration system. This approach prevents anaerobic clogging of the piping, a common issue in poorly designed RAS facilities.

In case of applications in aquaculture, as well as in most industrial applications slope assemblies of pipes are needed to ensure a system level freely flow.

In practice for safety reasons, it is recommended that installation of pipes for sewage to be made bigger slopes than the minimum one to ensure the flow rate higher than the minimum speeds of autocleaning but not higher than the maximum permitted speed.

Sizing evacuation system for the wastewater is well done when the slope of the installation has ensured a degree of filling the maximum permissible but a flow rate within acceptable limits.

CONCLUSIONS

The present research highlights that the performance of a recirculating aquaculture system depends not only on the quality of the equipment but, more importantly, on the hydraulic synergy between its components.

In RAS systems to increase efficiency and sustainability, there must be a constant concern in searching for new solutions and adopting them at the current standards.

By integrating the prefiltering equipment on the route of wastewater discharge circuit, numerous studies have shown that it can achieve a significant reduction in the concentration of solids in the water at low operating costs.

A proper sizing of inlet pipes and drain the RAS will contribute significantly to the proper functioning of the system and hence reduce operating costs.

The transition from an inefficient system to one optimized through innovative technical solutions demonstrated that high stocking densities (specific to super-intensive systems) can be sustained long-term only through rigorous control of fluid dynamics.

Utilizing the radial flow settler as a pre-filtration stage represents a sustainable technical solution. It protects the biofilter from overloading, ensuring stable nitrification and, consequently, a safe living environment for pikeperch, a species known for its high sensitivity.

The success of the system is directly dependent on the accuracy of the hydraulic calculations. Correlating the pipe slope with the self-cleaning velocity eliminates major operational risks and reduces long-term maintenance costs. Implementing the UV sterilization unit (SUV) at a strategic point in the flow (after the removal of fine particles) ensures water with minimal bacterial load, which directly translates into higher survival rates and faster growth of the fish stock.

This paper demonstrates that adopting these technical solutions transforms aquaculture from an empirical activity into a controlled, predictable, and environmentally friendly industry, providing a replicable model for modern fish farms.

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ANALYSIS OF PRODUCTS OBTAINED BY PYROLYSIS-REVIEW
/
ANALIZA PRODUȘILOR OBȚINUȚI PRIN PIROLIZĂ-REVIEW

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ABSTRACT

This paper aims to analyze recent scientific contributions on the characteristics obtained from different pyrolysis regimes applied to a wide range of feedstocks. It also presents the main pyrolysis methods reported in the literature and analyzes the products derived from the pyrolysis process. The study highlights the characteristics and valorization potential of the resulting fractions—namely biochar, bio-oil, and synthesis gas (syngas)—emphasizing their role in sustainable resource management and the recovery of residual materials. Waste-derived materials are analyzed, such as animal manures, sewage sludge, and woody biomass, whose valorization through pyrolysis can address major environmental issues while generating economically valuable products. Through a structured comparison of published data, this work offers an updated perspective on the potential of pyrolysis as a key technology in sustainable resource management.

REZUMAT

Această lucrare își propune să analizeze contribuțiile științifice recente privind caracteristicile obținute în urma aplicării diferitelor regimuri de piroliză asupra unei game largi de materii prime. De asemenea, sunt prezentate principalele metode de piroliză raportate în literatura de specialitate și sunt analizați produșii rezultați din acest proces. Studiul evidențiază caracteristicile și potențialul de valorificare al fracțiilor rezultate — respectiv biochar, bio-ulei și gaz de sinteză (syngas) — subliniind rolul acestora în managementul durabil al resurselor și în recuperarea materialelor reziduale. Se analizeaza materiale provenite din deșeuri, precum dejecțiile animale, nămolurile de epurare și biomasa lemnoasă, a căror valorificare prin piroliză poate contribui la abordarea unor probleme majore de mediu, generând totodată produse cu valoare economică. Printr-o comparație structurată a datelor publicate, această lucrare oferă o perspectivă actualizată asupra potențialului pirolizei ca tehnologie-cheie în managementul durabil al resurselor.

INTRODUCTION

As global interest in circular resource use intensifies, understanding which feedstocks are suitable for pyrolytic transformation becomes essential for both industrial optimization and environmental sustainability. A diverse array of solid and semi-solid materials—ranging from agricultural residues and forestry biomass to plastics, tires, and various organic wastes—can undergo controlled thermal decomposition in the absence of oxygen. Their physicochemical characteristics strongly influence product distribution, energy yield, and catalytic upgrading potential.

Thermochemical conversion of biomass and organic residues has gained substantial scientific and industrial attention in recent years due to the urgent need for sustainable energy carriers, carbon-neutral materials, and environmentally responsible waste-management strategies. Pyrolysis—the thermal decomposition of organic matter in the absence of oxygen—has emerged as one of the most flexible and scalable technologies for transforming diverse feedstocks into value-added products. Depending on the process conditions, pyrolysis produces three main product streams: bio-oil, biochar, and non-condensable gases, each with specific applications in renewable energy, soil enhancement, carbon sequestration, catalysis, chemical manufacturing, and materials engineering *(Bridgwater, 2012; Mohan et al., 2006).*

A defining advantage of pyrolysis lies in its ability to process a wide variety of biomass and waste materials, ranging from traditional lignocellulosic feedstocks to more challenging or heterogeneous residues.

Sources such as agricultural crop residues (straw, husks, pruning waste), forestry biomass, energy crops, animal manure, poultry litter, sewage sludge, food waste, algae, municipal solid waste fractions, and numerous industrial by-products have been successfully pyrolyzed for fuel, material, or environmental applications *(Chen et al., 2021; Kan et al., 2016; Fonts et al., 2012).* The physicochemical diversity of these feedstocks—including variations in lignin/cellulose content, ash composition, protein fraction, moisture, and inherent catalytic minerals—strongly influences product distribution and quality. Consequently, understanding feedstock-dependent behavior has become a critical research focus, especially within the framework of the circular bioeconomy, where converting low-value or problematic wastes into high-value products contributes to climate mitigation and resource recovery *(Pham et al., 2015; Zhang et al., 2019*).

Pyrolysis also demonstrates strong compatibility with waste-to-energy and waste-to-resource strategies because many feedstocks unsuitable for combustion or biochemical conversion can be thermochemically valorized after minimal pretreatment. High-ash or nitrogen-rich materials such as sewage sludge or animal manure, as well as wet biomass pre-treated through drying, torrefaction, or mechanical dewatering, have shown promising yields and product characteristics in several studies *(Fonts et al., 2012; Liu et al., 2020).* This feedstock flexibility positions pyrolysis as a cornerstone technology in integrated resource-management systems.

Recent technological developments have significantly improved the selectivity, efficiency, and environmental performance of pyrolysis processes. Innovations such as intermediate pyrolysis, microwave-assisted pyrolysis, catalytic pyrolysis, co-pyrolysis, autothermal pyrolysis, and solar-driven pyrolysis offer enhanced control over reaction pathways and product upgrading *(Dhyani and Bhaskar, 2018; Neves et al., 2011).* These approaches enable the production of tailor-made products:

- upgraded bio-oil with reduced oxygen content and improved stability,
- engineered biochars with optimized surface functionality for soil remediation, adsorption, or electrochemical applications, and
- cleaner syngas suitable for catalytic conversion into hydrogen or platform chemicals.

Despite these advancements, predicting and optimizing product yields remains challenging due to the complex network of primary and secondary reactions governed by feedstock structure, mineral matter, heating rate, temperature, vapor residence time, and catalytic interactions. Comparative evaluations of slow, fast, intermediate, catalytic, and co-pyrolysis are therefore necessary to identify performance trends and process-specific advantages. A deeper understanding of how different biomasses behave under various pyrolytic regimes is essential for designing efficient, scalable systems and maximizing product valorization across energy, environmental, and industrial domains.

MATERIALS AND METHODS

Classification of Pyrolysis Methods

2.1 Slow Pyrolysis

Slow pyrolysis is generally defined by low heating rates (often in the range of ~5–20 °C/min) and long solid residence times (from minutes up to several hours), with operating temperatures typically between ~350 and ~600 °C *(Jarzak et al, 2024, Vieira et al., 2020).*

Under such thermal conditions, devolatilization proceeds gradually, allowing for extensive secondary reactions that favor char (biochar) formation rather than volatiles or gases — making slow pyrolysis the “go-to” method when the objective is stable carbon-rich biochar, for uses such as soil amendment or carbon sequestration *(Bezuszko et al, 2025, Kumar and Penwar, 2024)*

2.2 Fast Pyrolysis

Fast pyrolysis employs rapid heating rates (>100 °C/s) and short vapor residence times (typically <2 s), with temperatures around 450–550 °C. This approach is designed to maximize bio-oil yield, often achieving 60–70 wt% (moisture content) under optimized conditions. The process requires finely ground biomass and highly efficient heat transfer, commonly implemented in fluidized-bed or circulating-bed reactors *(Hoekstra, Ph.D. Thesis,2011).* The process requires finely ground biomass to ensure uniform and rapid heating, as well as highly efficient heat transfer. Reactor configurations that are commonly employed include **fluidized-bed reactors** and **circulating-fluidized-bed reactors**, which provide excellent heat distribution and allow continuous or semi-continuous operation ***(Oghyanous and Eskicioglu, 2025)***

2.3 Flash Pyrolysis

Flash pyrolysis is considered an extreme variant of thermal biomass conversion, distinguished by very high heating rates, ultra-short vapor residence times, and high operating temperatures — conditions under which organic macromolecules are rapidly cracked to yield vapors that, if quickly quenched, condense into liquid fractions or yield syngas, depending on downstream handling *(Jerzak et al., 2024; Toroman, 2025).* Typical reported parameters for flash pyrolysis include heating rates on the order of **≥ 1000 °C/s**, vapor residence times well below one second (often < 0.5–1 s), and process temperatures ranging from **~500 °C up to 900–1200 °C**, depending on the desired product output (liquid, gas, or intermediates) *(Basu,2010).*

Under these extreme conditions, flash pyrolysis strives to minimize char formation and maximize production of pyrolysis vapors — potentially leading to very high yields of **bio-oil or condensable liquids** (in some reports > 75 wt%) as well as **light volatiles or synthesis gases**, especially when further catalytic or thermal upgrading is implemented (*Kumar and Penwar, 2024)*.

2.4 Catalytic Pyrolysis

Catalytic pyrolysis introduces catalysts—such as zeolites, metal oxides, or bio-based catalysts—to promote selective cracking, deoxygenation, and aromatization of pyrolysis vapors. It can be integrated directly into the reactor (in-situ) or performed downstream (ex-situ). Catalysis improves the quality of bio-oil by reducing oxygen content and increasing hydrocarbon selectivity, but often at the expense of liquid yield.

Catalysts may be used in-situ (mixed with biomass in the reactor) or ex-situ (vapors pass downstream through a catalytic zone). The catalytic approach can significantly improve the quality of the bio-oil by lowering oxygenated compounds, reducing acidity and water content, increasing hydrocarbon (especially aromatic) fraction, and generally enhancing the energy density (higher H/C ratio) *(Mishra et. al, 2022).*

However, these benefits often come at a cost: the **total liquid yield tends to decrease** relative to non-catalytic pyrolysis, because more volatiles are cracked into lighter gases or coke, or transformed into char*. (Gholizadeh et al, 2023)***.** Also, catalyst deactivation (e.g. by coke deposition) remains a major challenge, especially in continuous operation or when using biomass with high ash or impurities *(Kumar et al., 2022)*

2.5 Microwave-Assisted Pyrolysis

Microwave-assisted pyrolysis (MAP) uses electromagnetic radiation (microwaves) to heat biomass **volumetrically and internally**, in contrast to conventional external heating. This allows more **uniform and rapid heating**, reducing thermal gradients, improving energy efficiency, and enabling processing of **wet or high-moisture feedstocks** (e.g. sewage sludge, algae, wet waste) with reduced pre-drying requirements. *(Li et all, 2022)*

Because heating is volumetric and fast, MAP can shorten reaction times and potentially shift product distribution, depending on biomass properties, microwave absorbers, and reactor design. In some cases, this method can lead to favorable yields of biochar, bio-oil, or syngas from feedstocks that would otherwise be challenging for conventional pyrolysis *(de Morais et al., 2023).*

However, the final product distribution strongly depends on the presence and type of **microwave susceptors or absorbers**, the dielectric properties of biomass, moisture content, and reactor geometry. These parameters influence heating uniformity, internal energy absorption, and thus cracking pathways. *(Ke et al., 2024).*

Pyrolysis is producing three primary product streams: biochar, bio-oil, and syngas. The proportions and characteristics of these products depend strongly on process variables such as temperature, heating rate, residence time, and feedstock composition. Understanding the composition and functional behavior of these fractions is essential for optimizing pyrolysis systems and valorizing biomass-derived resources in sustainable energy, agriculture, and industrial chemistry.

Biochar represents the solid carbonaceous residue formed through the rearrangement and carbonization of lignocellulosic structures. Due to its high aromatic carbon content, stability, and porous architecture, it is widely studied for soil enhancement, carbon sequestration, and its potential as a precursor for advanced carbon materials.

Its structure is dominated by aromatic carbon rings, which makes it chemically stable and resistant to biodegradation.

Its typical composition includes a high proportion of fixed carbon, which can reach 60–90%, along with various minerals contained in the ash fraction, such as calcium, potassium, magnesium, silicon, and phosphorus *(Mohan et al., 2006; Lehmann and Joseph, 2015).* In addition to these major components, biochar contains small amounts of hydrogen, nitrogen, and oxygen, reflecting the profound transformations of the lignocellulosic structure that occur during pyrolysis *(Demirbaş, 2009).* Its microstructure is characterized by high porosity, consisting of micro- and mesopores that provide a large specific surface area and strong adsorptive capacity *(Bridgwater, 2012).*

Due to its stable aromatic architecture, biochar exhibits remarkable resistance to degradation and remains in soil for long periods, contributing to durable carbon sequestration *(Lehmann and Joseph, 2015).* Its high porosity gives it the ability to adsorb nutrients, heavy metals, and organic compounds, making it useful in soil remediation and the improvement of natural soil fertility *(Mohan et al., 2006).* Furthermore, soil amendment with biochar enhances aeration, increases water retention capacity, and improves cation-exchange capacity, thus having a positive impact on agricultural productivity, especially on degraded or sandy soils (Laird, 2008).

Beyond agricultural applications, biochar is a valuable feedstock for the carbon industry. Due to its porous structure and high carbon content, it can be used as a precursor for producing activated carbon, electrodes for batteries or supercapacitors, and support materials for catalysts employed in advanced chemical and energy processes *(Bridgwater, 2012; Demirbaş, 2009).* These characteristics make biochar a multifunctional product essential both in the bioeconomy and in modern environmental technologies.

Table 1

Values of Biochar characteristics obtained from different sources

Feedstock (type)	Typical pyrolysis temperature / conditions	Biochar yield (wt% of dry feed) / yield remarks	C (wt%) or fixed-C / general carbon content	H/C (atomic)	O/C (atomic)	Ash (or mineral / inorganic) content or remarks	Source(s)
Wood sawdust / woody biomass (general plant-biomass)	Generally, pyrolysis T 400–700 °C in many studies	Biochar yield decreases with increasing T; in wood-based chars yield often moderate (data vary by species)	Woody biochars often show high fixed carbon (post-pyrolysis) and low ash (if feed was clean wood) — specific studies report C content rising after pyrolysis, sometimes >70–90% (on ash-free basis)	H/C and O/C decrease with T → more aromatic stable carbon in char	—	Ash generally low (except if wood contaminated or bark included) → favorable for carbon-rich biochar applications (carbon sequestration, activated carbon, etc.)	*Novac et al., 2009 Novak et al, 2013*
Sewage sludge (100% sludge)	300–900 °C (various T)	~64.3% at 300 °C → ~46.7% at 700 °C (dry sludge basis)	37.15 wt% C at 300 °C → 25.23 wt% C at 900 °C	H/C ~1.41 (low T) → ~0.30 (at 900 °C) (	O/C ~0.27 (low T) → ~0.03 (at 900 °C)	Very high mineral/ash; in some cases, ash-rich biochar with significant Si, Al, Fe oxides accumulated at high T	*Zhang et al, 2015 Wu et al., 2024*
Poultry litter (animal-waste)	460–530 °C (fast pyrolysis bubbling fluidised bed)	~32 wt% (in one fluidised-bed FP study)	47.0% (at 460 °C), 48.5% (at 530 °C) C in biochar (dry basis) in that study	H/C ~0.51 (460 °C), ~0.42 (530 °C)	O/C ~0.12 (460 °C), ~0.06 (530 °C) in same study	Very high ash: biochar ash ~39–43% in that study; poultry-litter chars often >50% ash in other studies	*Pandey et al., 2019 Yang et al., 2024*

Feedstock (type)	Typical pyrolysis temperature / conditions	Biochar yield (wt% of dry feed) / yield remarks	C (wt%) or fixed-C / general carbon content	H/C (atomic)	O/C (atomic)	Ash (or mineral / inorganic) content or remarks	Source(s)
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						depending on feed & pyrolysis.	
Manure-based waste (livestock manure other than poultry / e.g. cow dung + manure blends)	400 °C pyrolysis in comparative study	Biochar yield for cow dung ~41% at 400 °C (	Lower fixed carbon than woody chars; due to high ash/mineral content often considered less carbon-rich char — exact C% varied depending on feed and treatment.	H/C & O/C likely lower (more aromatic C) but: due to mixed organic/mineral content, heterogeneity high — not always reported clearly.	—	Ash/mineral content often high; these chars tend to have significant nutrient and mineral load (Ca, P, K etc.), thus good for soil amendment rather than high-purity carbon applications.	*Kukwa et al., 2025 Dzvene, 2017*

Biochar composition varies mainly with feedstock type and pyrolysis severity. Lignocellulosic materials produce chars with high fixed carbon, low ash, and highly aromatic structures, making them stable and suitable for long-term carbon sequestration. Sludge, manure, and industrial residues yield mineral-rich chars with lower carbon content and higher concentrations of nutrients or metals, which enhances soil fertility but may require contaminant monitoring. Overall, temperature governs aromaticity and functional groups, while the feedstock determines the elemental and mineral profile, resulting in biochars with diverse properties and applications.

***Bio-oil*,** the liquid condensate of volatile pyrolysis products, is an oxygen-rich and chemically diverse mixture that can serve as an intermediate for bio-based fuels, chemicals, and materials *(Wang et al., 2013; Tóth et al., 2024).* It represents a complex, oxygen-rich mixture of hundreds of organic compounds, including sugars, furans, organic acids, aldehydes, ketones, and phenolic derivatives). The composition of bio-oil is strongly influenced by the type of feedstock, its biochemical constituents (cellulose, hemicellulose, lignin, proteins, and lipids), and the pyrolysis conditions, such as temperature, heating rate, and vapor residence time *(Tóth et al., 2024).*

Fast pyrolysis, characterized by high heating rates and short vapor residence times (typically 450–550 °C), is optimized to maximize bio-oil yields, often producing 50–70 wt.% liquids from dry lignocellulosic feedstocks *(Lee et al., 2010; Wang et al., 2013)*. In contrast, slow pyrolysis produces lower liquid yields, favoring char formation *(Tóth et al., 2024).* Bio-oils from lignocellulosic materials are dominated by oxygenated compounds: phenolics from lignin, anhydro sugars like levoglucosan from cellulose, and furans and low-molecular-weight acids from hemicellulose *(Wang et al., 2013; Lee et al., 2010).* Nitrogen- and sulfur-containing compounds can be significant in bio-oils derived from protein- or algae-rich feedstocks, including manures and sludges *(Moško et al., 2021).*

Table 2

Values of Bio oil characteristics obtained from different sources

Feedstock (type)	Typical pyrolysis temperature / conditions	Bio-oil yield (wt% of dry feed)	Major chemical classes	Key representative compounds	Source(s)
Wheat straw (agricultural residue)	Fast pyrolysis 450–550 °C	55–65 wt%	Similar to rice straw: acids, aldehydes, ketones, phenolics, furans	Levoglucosan, acetic acid, 5-hydroxymethylfurfural (HMF), phenolic oligomers	*Tóth et al., 2024; Pandey et al., 2024*
Elm / hardwood	500–700 °C	30–45 wt%	Aromatic phenolics, some ketones, acids	Guaiacol, syringol, phenol, small carboxylic acids	*Wang et al., 2013; Tóth et al., 2024*
Pine / softwood	400–700 °C	30–50 wt%	Phenolics (from lignin), some ketones and acids	Guaiacol, syringol, catechol, acetic acid	*Wang et al., 2013; Lee et al., 2010*
Sewage sludge	400–600 °C	20–30 wt%	Nitrogen- and oxygen-containing organics, small phenolics, carboxylic acids	Amines, fatty acids, carboxylic acids, phenols	*Moško et al., 2021;*
Poultry litter	460–530 °C (fluidized bed)	25–35 wt%	Phenolics, nitrogenated organics, carboxylic acids	Guaiacol, phenol, pyrroles, acetic acid	*Pandey et al., 2024*
Food waste / MSW (mixed organic waste)	350–750 °C	20–40 wt%	Diverse oxygenates, sugars, acids, some aromatics	Levoglucosan, acetic acid, furfural, phenol, other aldehydes	*PubMed 2017; Environmental Sci. & Pollution Research 2024*

Bio-oil obtained through pyrolysis represents a versatile but chemically complex intermediate whose composition depends strongly on feedstock characteristics and operating conditions. Although its high oxygen content and instability present challenges, continued advancements in catalytic upgrading, fractionation, and process optimization are steadily improving its viability as a renewable source of fuels and value-added chemicals. Bio-oil therefore remains a key component in integrated biomass valorization strategies and a promising pathway toward sustainable, low-carbon energy systems.

Syngas, the non-condensable gaseous product generated during biomass pyrolysis, is a combustible mixture primarily composed of carbon monoxide (CO), carbon dioxide (CO_2), hydrogen (H_2), methane (CH_4) and smaller quantities of light hydrocarbons (C_2–C_4) (Wang et al., 2013; Tóth et al., 2024). Its composition depends strongly on the feedstock properties, such as lignocellulosic content, protein and lipid fractions, and ash chemistry, as well as on operational parameters including temperature, heating rate, and vapor residence time *(Lee et al., 2010; Tóth et al., 2024)*. At typical pyrolysis temperatures of 400–700 °C, the generation of syngas results from thermal cracking, decarboxylation, and secondary reforming reactions involving cellulose, hemicellulose, lignin, and other biogenic components *(Wang et al., 2013)*.

Table 3

Values of Syngas characteristics obtained from different sources

Feedstock (Category)	Typical pyrolysis temperature	Syngas yield (wt% or vol%)	Main components (vol%)	Notable features	Academic source(s)
Wheat straw (agricultural residue)	450–550 °C (fast pyrolysis)	10–20 wt%	CO (20–35%), CO_2 (25–45%), H_2 (5–15%), CH_4 (2–10%), light hydrocarbons (C_2–C_4: 1–5%)	Moderate H_2 due to devolatilization; high CO_2 from hemicellulose	*Tóth et al., 2024; Wang et al., 2013*
Pine / softwood	500–700 °C	10–18 wt%	CO (25–40%), CO_2 (25–40%), H_2 (5–15%), CH_4 (3–10%)	Higher lignin increases CH_4 formation	*Wang et al., 2013*
Hardwood	500–700 °C	10–15 wt%	CO (20–35%), CO_2 (30–45%), H_2 (5–12%), CH_4 (2–6%)	Gas richer in CO_2 due to oxygen-rich cellulose	*Wang et al., 2013*
Sewage sludge	500–700 °C	20–35 wt% (higher due to volatiles & proteins)	CO (10–20%), CO_2 (25–45%), H_2 (10–25%), CH_4 (5–15%), NH_3 traces, light hydrocarbons	Higher H_2 & CH_4 due to proteins and lipids; N-containing gases	*Moško et al., 2021*
Poultry litter	450–550 °C	15–25 wt%	CO (15–30%), CO_2 (30–50%), H_2 (10–18%), CH_4 (5–12%)	Nitrogenated gases (NH_3, HCN) appear	*Pandey et al., 2024*
Food waste / MSW	400–750 °C	20–30 wt%	CO (20–35%), CO_2 (25–40%), H_2 (8–20%), CH_4 (5–12%)	Highly variable composition based on waste matrix	*Environmental Sci. & Pollution Research 2024*
Algae	450–600 °C	20–35 wt%	CO (15–30%), CO_2 (25–45%), H_2 (10–25%), CH_4 (5–15%), small N-heterocycles	High H_2 due to protein decomposition; more NH_3	*Algae pyrolysis reviews (2023–2024)*

Lignocellulosic feedstocks usually produce syngas dominated by CO and CO_2, with moderate fractions of H_2 and CH_4 formed through secondary cracking of volatile intermediates (Tóth et al., 2024). In contrast, protein- and lipid-rich materials such as sewage sludge, poultry litter, algae, and food waste tend to generate higher levels of H_2, CH_4, and nitrogen-containing light gases (*Moško et al., 2021; MDPI Sustainability, 2019*), reflecting their biochemical and mineral composition. Higher pyrolysis temperatures increase H_2 formation by enhancing *dehydrogenation* and reforming pathways, while reducing heavier oxygenated vapors (*Lee et al., 2010*).

Due to its calorific value and reactive composition, pyrolysis syngas can be used for heat and power generation, or upgraded to serve as a precursor for Fischer–Tropsch synthesis, methanol production, hydrogen-enriched gas streams, and other catalytic processes *(Wang et al., 2013).* As a flexible and renewable gaseous fuel, syngas plays an essential role in biomass valorization strategies, supporting sustainable pathways for low-carbon energy and chemical production *(Tóth et al., 2024).*

CONCLUSIONS

1. **Feedstock composition strongly influences the chemical profile of pyrolysis products.** Lignocellulosic materials generate biochar with high fixed carbon and aromaticity, bio-oils rich in anhydro sugars and phenolics, and syngas dominated by CO and CO_2. In contrast, protein- and mineral-rich feedstocks (sludge, manures, algae) produce chars with high ash and nutrient content, bio-oils containing nitrogenated compounds, and syngas with elevated H_2, CH_4, and N-containing gases.
2. **Biochar exhibits the highest chemical stability among pyrolysis products**, with carbon-rich structures suitable for soil amendment, carbon sequestration, and adsorbent applications. Its

physicochemical properties (surface area, mineral content, pH) reflect both **feedstock origin** and **pyrolysis severity**, creating a wide spectrum of functional materials.

3. **Bio-oil is an energy-dense but oxygen-rich and chemically unstable liquid**, requiring upgrading techniques such as hydrodeoxygenation, esterification, or catalytic cracking to improve storage stability and convert it into high-quality transportation fuels or platform chemicals. Its composition mirrors the decomposition pathways of major biomass polymers and varies significantly with process conditions.
4. **Syngas serves as a versatile gaseous fuel and chemical intermediate**, with composition dependent on temperature-driven secondary cracking and reforming reactions. After cleaning, pyrolysis syngas can be used for heat, power, or synthetic fuel production via catalytic processes such as **Fischer–Tropsch synthesis**, contributing to flexible and low-carbon energy systems.

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USE OF MONITORING SYSTEMS FOR FUNCTIONAL PARAMETERS OF EQUIPMENT IN MECHANIZED TECHNOLOGIES FOR FRUIT GROWING
/
UTILIZAREA SISTEMELOR DE MONITORIZARE A PARAMETRILOR FUNCȚIONALI LA ECHIPAMENTE DESTINATE TEHNOLOGIILOR MECANIZATE ÎN POMICULTURĂ

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ABSTRACT

The mechanization of work in fruit growing has evolved considerably in recent decades, amid increasing demands for productivity, quality of work and sustainability of crop interventions. This paper analyzes the role of functional parameter monitoring systems in optimizing the operation of equipment used in mechanized technologies used in fruit growing and presents several monitoring system implementations carried out within INMA Bucharest for three types of equipment: ETR – root cutting equipment, ERI – inflorescence thinning equipment and PP – self-moving fruit growing platform. The analyzed monitoring systems target functional parameters such as: traction force, pressures in hydrostatic systems, rotation speed and control of the movement trajectory. The results show that the integration of sensors and digital systems contributes to increasing the precision of the work, reducing mechanical stress, improving operator safety and optimizing operating costs. The study confirms that real-time monitoring is an essential direction for the modernization of technologies in fruit growing in order to increase the sustainability of interventions in modern fruit plantations.

REZUMAT

Mecanizarea lucrărilor în pomicultură a evoluat considerabil în ultimele decenii, pe fondul creșterii cerințelor privind productivitatea, calitatea lucrărilor și sustenabilitatea intervențiilor asupra culturilor. Prezenta lucrare analizează rolul sistemelor de monitorizare a parametrilor funcționali în optimizarea funcționării echipamentelor utilizate în tehnologiile mecanizate utilizate în pomicultură şi prezintă câteva realiză de sisteme de monitorizare realizate în cadrul INMA București pentru trei tipuri de echipamente: ETR – echipamentul pentru tăierea rădăcinilor, ERI – echipamentul pentru rărirea inflorescențelor și PP – platforma pomicolă autodeplasabilă. Sistemele de monitorizare analizate vizează parametri funcţionali precum: forța de tracţiune, presiunile din sistemele hidrostatice, viteza de rotaţie, controlul traiectoriei de deplasare. Rezultatele arată că integrarea senzoristicii și a sistemelor digitale contribuie la creșterea preciziei lucrărilor, la reducerea solicitărilor mecanice, la îmbunătățirea siguranței operatorilor și la optimizarea costurilor de exploatare. Studiul confirmă faptul că monitorizarea în timp real reprezintă o direcție esențială pentru modernizarea tehnologiilor în cadrul pomiculturii în vederea creșterii sustenabilității intervențiilor în plantaţiile pomicole moderne.

INTRODUCTION

A fundamental principle of sustainable development is the adoption of strategic and integrated management, capable of truly including the dimensions of sustainability. An essential criterion in this regard is the guarantee that future generations will not have living conditions inferior to those of the present. To achieve this objective, it is necessary to ensure equitable, long-term access to basic resources for all generations (*Păduraru T.*, 2023). The principles of sustainable development represent the foundation of a responsible and balanced future for the entire society and include four major dimensions: environmental protection, economic development, social responsibility and strengthening partnerships.

The principles set out are closely linked to the Sustainable Development Goals (SDGs) 2015–2030, adopted by the United Nations General Assembly and brought together under the name of the 2030 Agenda, which constitutes a global framework for building a more equitable and sustainable future. The 17

Sustainable Development Goals (SDGs), grouped into six important areas, address the main challenges of contemporary society, such as poverty, inequalities, climate change, innovation, economic development, environmental degradation, peace and justice (Fig. 1). The assessment of the degree of achievement of the 17 SDGs was carried out based on national indicators monitored since 2016 (the latest data), revealing a level of achievement of 62.1%, according to data from the National Institute of Statistics.

Fig. 1 – Summary of sustainable development areas according to the SDGs 2015–2030 objectives

The general concept of fruit growing has undergone a profound transformation, moving from the trend of industrialized fruit growing, which consumes a lot of inputs, to a sustainable fruit growing system that promotes the cultivation of the land by those means that ultimately lead to achieving a balance between agroecosystems and the environment.

The technologies for mechanizing work in fruit growing have evolved considerably in recent decades, amid increasing demands for productivity, quality of work and sustainability of crop interventions. Currently, modern technologies increasingly integrate monitoring systems that allow the measurement and control of functional parameters of equipment – forces, pressures, vibrations, working angles, energy consumption or stability, etc. These data represent the basis for optimizing settings, preventing failures and instantly adapting work processes to the specific conditions in fruit orchards.

In the context of the digitalization of agriculture and the European orientation towards intelligent mechanization, the use of sensors and monitoring tools is becoming a critical component of modern fruit growing technologies. In fruit growing, where the work is often sensitive, repetitive and with a direct impact on the physiology of the plantation, monitoring of functional parameters offers the advantage of an accurate, reproducible and energy-efficient intervention (*Khurshid T., Sanderson GP.*, 2023) .

Under such conditions, the development of an innovative technology supported by a series of efficient technical equipment that would mechanize a significant part of the maintenance work in fruit growing, the final result leading to the production of products in increased quantities, safe and of superior quality.

Recent research shows a rapid transition from isolated monitoring solutions to integrated IoT-AI systems that collect real-time data from the orchard and provide automated decision support for irrigation, thinning, treatments and harvesting. In current practices, UAVs (drones) and multispectral/hyperspectral images combined with neural networks are becoming leading tools for detecting vegetation status, estimating production and identifying areas affected by water stress or diseases (*Popescu D.*, et. al. 2023)

Another expanding field is orchard robotics used for thinning, weeding/maintenance and harvesting using computer vision systems, path planning and multiple manipulators; recent achievements reporting significant progress although efficiency under real conditions still remains a challenge (*Navone A., Martini M., Chiaberge M.*, 2025).

Monitoring the functional parameters of the equipment used in fruit growing is a critical step in ensuring a safe, efficient and adapted work process to the real conditions in the field. Parameters such as

working force, hydraulic pressures and flows, working speeds, vibrations, assembly stability, energy consumption or effective working depth provide an objective picture of how the equipment interacts with the soil, trees or the working environment. The study carried out in the article presents a critical analysis of some types of equipment existing at national and global level, highlighting their advantages and limitations.

MATERIAL AND METHOD

This paper analyzes the applicability of monitoring systems on three types of representative equipment for the maintenance of fruit plantations, as follows: Technical equipment for cutting tree roots - ETR; Technical equipment for thinning tree inflorescences - ERI; Self-moving fruit platform - PP, highlighting how the measured data contributes to improving technical performance, increasing operator safety and establishing sustainable technologies.

Real-time knowledge of these values allows for the rapid identification of overloads, optimization of work settings and appropriate adjustment of active mechanisms, thus contributing to increasing the reliability of the equipment and preventing failures. At the same time, the analysis of functional parameters facilitates the adaptation of equipment to the high variability specific to fruit plantations / orchards - differences in soil, humidity, tree age, branch densities or relief - essential aspects for maintaining the quality of the work and reducing the impact on the environment.

Monitoring also contributes to improving operation and increasing safety levels by detecting conditions in which equipment may exceed the permitted stability or load limits. In the long term, the recorded data allows for the substantiation of predictive maintenance programs, the optimization of resource consumption and the development of more efficient technologies better adapted to the requirements of modern fruit growing. In this context, the integration of monitoring systems is not only a technical tool but also a strategic component in the process of digitalization and modernization of the horticultural sector.

The ETR experimental model (Fig. 2) is designed and developed within INMA Bucharest to optimize the maintenance process of fruit plantations, contributing to the development of methods to limit the capacity of trees to produce unproductive shoots, which creates problems for fruit tree crops by reducing production yield. Most often, these problems occur due to temperature changes, extreme variations in humidity, lack or excess of nutrients in the soil. Controlled mechanical removal of roots is necessary when the yield of fruit plantations is reduced, because all nutrients are consumed for vegetative growth and less for fruiting and in order to reduce the costs of technological works in plantations.

The ERI experimental model (Fig. 3) is also designed and developed within INMA Bucharest to optimize the maintenance process of fruit plantations, contributing to a better distribution of vegetative and generative resources. Development of a fruit tree crown maintenance equipment for constant quantitative and superior qualitative fruiting, technology that aims, in addition to fruiting pruning, to reduce the amount of inflorescences in fruit tree plantations (apple, peach, plum, cherry). By reducing the number of flowers, the tree, which is the owner of the food reservoir, provides the nutrients necessary for the development of a reduced number of fruits, as a result, they will develop better dimensionally and implicitly in weight, determining an annual fruit production that is constant quantitatively and superior qualitatively, to ensure the population's consumption needs. Thus, fruit production will be on a level year after year, also determining its better valorization and increasing farmers' benefits. Thinning can be done mechanically, by breaking off excess flowers, or chemically, by spraying the trees with certain substances, which selectively attack only certain flowers, depending on their development phase. Given that the use of chemicals is undesirable, being also expensive, the mechanical solution carried out with the help of specialized equipment for this operation, is the most appropriate. Trends in the field aim to increase automation and the use of artificial intelligence, contributing to reducing production costs, improving fruit quality and ensuring sustainable and ecological agriculture (*Matache, MG, et. al.*, 2024).

The experimental model PP, (Fig. 4) Self-propelled fruit-growing platform intended for carrying out fruit-growing works – also designed and manufactured within INMA Bucharest – is a self-propelled platform type equipment for working in fruit crops that becomes an extremely useful tool, being used in all phases of tree development by facilitating the carrying out of works, such as: tree cleaning and fruiting cuts, fruit thinning (as an operation to complete or finalize the thinning of inflorescences), stretching/tightening anti-hail protection nets, monitoring fruit production and harvesting them.

Fig. 2 - Technical equipment for cutting tree roots (ETR)

Fig. 3 - Technical equipment for thinning tree inflorescences (ERI)

Fig. 4 - Self-moving fruit platform (PP)

The adoption of modern and efficient technical solutions is an essential condition for innovative orchard maintenance technology to meet the current requirements of producers, ensuring efficiency, safety and adaptability to the real needs of farms. The developed equipment integrates advanced design, execution and testing concepts, aligned with the principles of Agriculture 4.0, which aims to reduce technological, investment and operational risks, as well as increase the level of security in use.

In this context, the ETR root cutting equipment is equipped with a system based on force transducers that monitor cutting resistance, in order to protect the active organ and prevent overloading or damage.

The ERI inflorescence thinning equipment uses an intelligent system for detecting floral volume, analyzing it and controlling the working regime of the thinning rotor. It also features elements for adapting the rotor position to the size and shape of the crown.

The PP self-propelled fruit-growing platform is equipped with a start-up, movement and trajectory control and command system , which contributes to safe operation and optimal positioning during work.

Based on the technical configuration presented and the parameters selected for monitoring, the following section analyzes the results obtained from the functional evaluation of equipment within the fruit plantation maintenance technology.

RESULTS

The results are structured according to the type of equipment and the monitored parameters, highlighting how each intelligent system contributes to optimizing the work process, increasing operational safety and improving technological efficiency. The interpretation of this data provides an objective basis for validating the proposed technical solutions and for formulating future development directions.

I. The intelligent system for monitoring the working resistance of the root cutting equipment (ETR), schematically presented in the form of a conceptual diagram in (Fig. 5), integrates a series of components for the real-time evaluation of the interaction between the active knife and the soil, consisting of:

- a cutting force measurement module, made by a load cell mounted in the area of the knife-holder arm;
- a set of hydraulic pressure and flow sensors, with a role in monitoring the demands on the hydraulic system and the effective penetration depth;
- a system for monitoring the working angle and knife position, based on linear and rotational position transducers;
- a data acquisition and storage unit, with the possibility of transmitting parameters to the operator.

The advantages of implementing this system are significant:

- allows precise adjustment of the working angle and depth depending on the type of soil and the age of the trees;
- reduces the risk of excessive strain on the knife and hydraulic system;
- contributes to the uniformity of root cutting, preventing damage to the root system and stem;
- provides useful data for predictive maintenance programs and for optimizing work cycles.

The main technical characteristics of the equipment:

- Equipment type: worn, 3-point hitch;
- Power source / power requirement: tractor with at least 80 HP on wheels;
- Maximum working depth: 500 mm;
- Working depth and width adjustment: hydraulic;
- Horizontal knife extension: 500 mm;

- Oblique inclination of the knife, for adjusting the working angle: 45°…70°;
- Overall dimensions:
  - Length: 875 mm;
  - Max. overall width: 2593 mm;
  - Min. overall width: 2093 mm;
  - Height: 2220 mm.
- Equipment weight, including ballast weight: approx. 600 kg

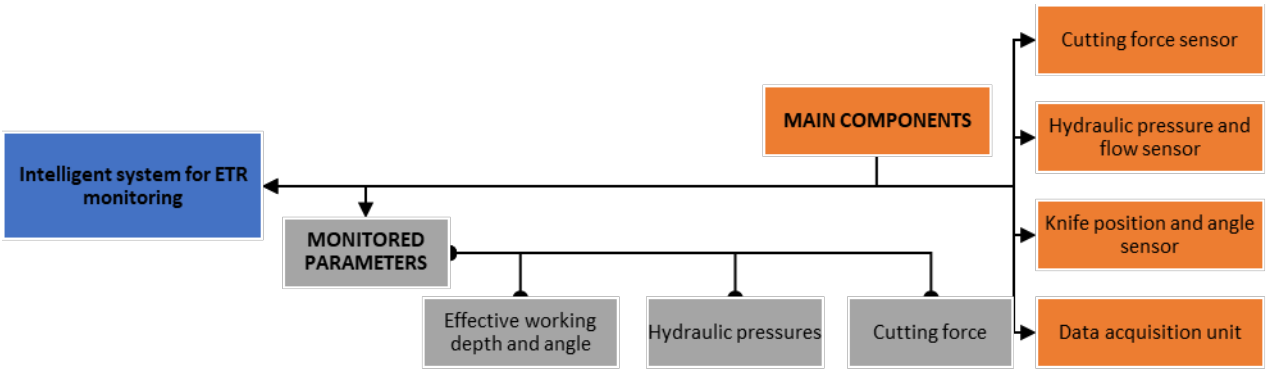

Fig. 5 – Conceptual diagram of the intelligent system intended to monitor the operation of ETR

II. The intelligent system associated with the ERI inflorescence thinning equipment, (Fig.6) has been developed to ensure a controlled operation adapted to the actual density of branches and inflorescences. The system structure includes:
- a module for monitoring the speed and drive torque of the active element, through speed sensors and torque transducers;
- a vibration and mechanical stress detection system to prevent overloads when in contact with branches;
- a set of position and lateral displacement sensors, which indicate proximity and distance to the tree crown;
- an electronic acquisition unit, capable of corroborating functional parameters with travel speed and vegetative conditions.

The advantages of using this intelligent system are obvious:
- automatically adjusts the intensity of the work depending on the density of the flowers and the flexibility of the branches;
- minimizes the risk of branch breakage or mechanical injury to the crown;
- contributes to the uniformity of the thinning process and the formation of a balanced productive potential;
- allows the recording of data necessary to optimize settings for different varieties and phenological stages.

The main technical characteristics of the equipment :
- Equipment type: mounted on the tractor's front linkage;
- Maximum working height: 3000 mm;
- Horizontal extension: 500 mm;
- Oblique tilt of the rotor, for adjusting the working angle, left / right: approx. 18°;
- Overall dimensions:
  - Length: 685 mm;
  - Width: 1600 mm;
  - Height: 3252 mm;
- Equipment weight: approx. 120 kg.

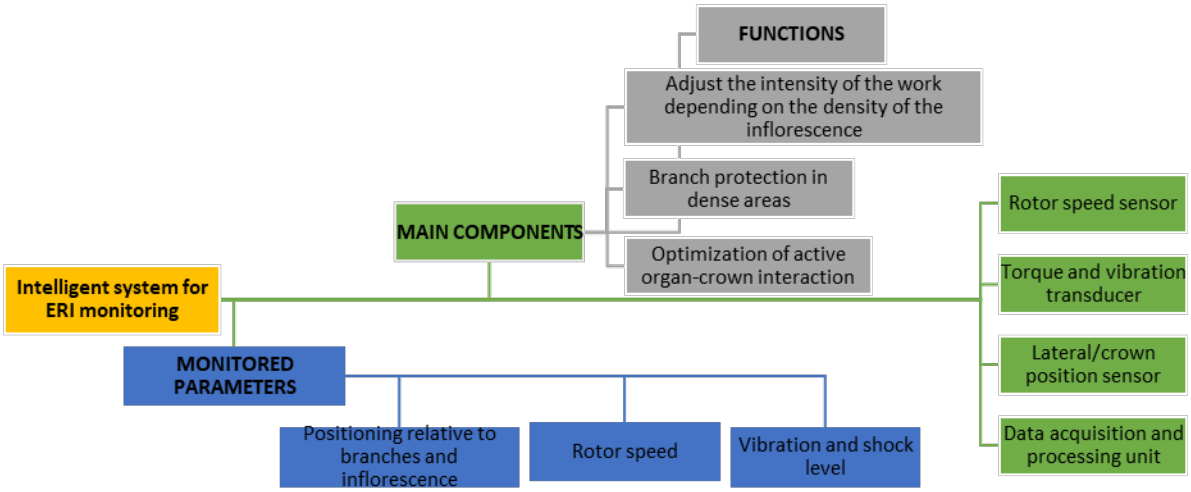

Fig. 6 – Conceptual diagram of the intelligent system for monitoring the operation of ERI

III. The intelligent system for driving the self-propelled fruit platform PP, (Fig. 7) for working in fruit plantations is mainly composed of the following components:

- a module for remotely starting the thermal engine by one of the operators on the platform (the positioning location is located in a different area than the classic driving position);
- the module for monitoring the position and direction of movement of the platform on the row of trees, using LiDAR technology;
- a joystick system for managing the direction of travel, placed on one of the platform's mobile walkways.

The advantages of using such an intelligent system are:

- can be operated by any of the people working on the platform;
- the platform can be moved and positioned as necessary so that the personnel can carry out the work in complete safety and optimal working conditions;
- eliminates the continuous presence of an operator who only manages the platform.

The main technical characteristics of the platform :

- Equipment type: mobile auto platform;
- Energy source: 45HP engine, supports movement and operation;
- Height of mobile platforms: h1 = 850 mm, h2 = 1350 mm, h3 = 1850 mm;
- Rear fork width, at the inner level of the rollers (for euro pallet): 1210 mm;
- Overall dimensions:
  - Length: 6000 mm;
  - Width: 1800 mm;
  - Working width: approx. 3000 mm;
  - Height: 2850 mm.
- Weight: approx. 2000 kg.

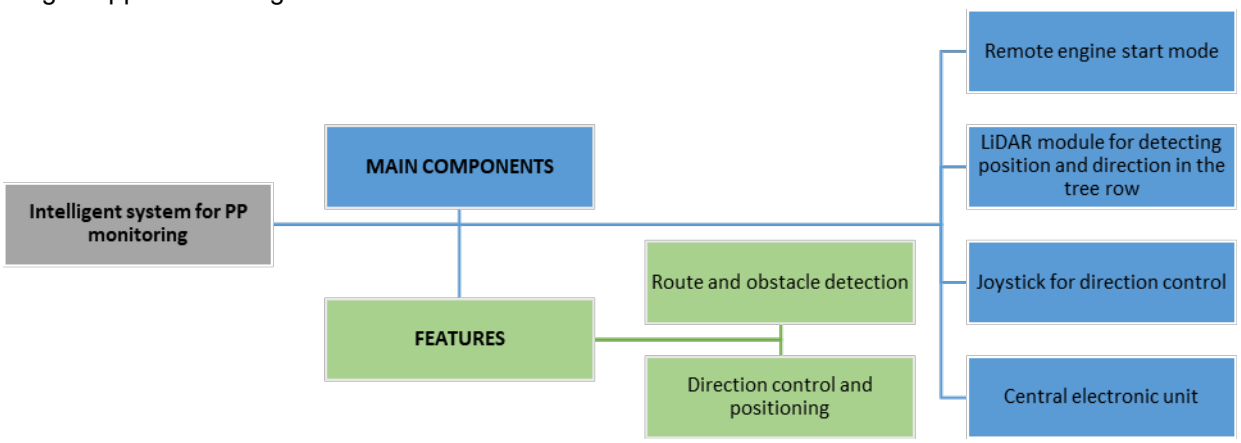

Fig. 7 – Conceptual diagram of the intelligent system for monitoring the operation of PP

The conceptual diagrams associated with the three pieces of equipment used in orchard maintenance technology highlight the architecture of intelligent monitoring systems and how they contribute to the optimal functioning of technological assemblies. For the orchard platform (PP), the diagram illustrates the integration of the remote start module, the LiDAR system for path detection and the control joystick, configured to ensure safe and precise movement along the rows of trees.

In the case of the root cutting equipment (ETR), the conceptual diagram shows the structure of the monitoring system composed of force sensors (force transducers), pressure and position, which allow the evaluation of mechanical stresses and the correct adjustment of the active organ. For the inflorescence thinning equipment (ERI), the diagram describes how the speed, vibration and position sensors are integrated to ensure a controlled and selective action on the crown.

Together, these diagrams provide a synthetic picture of how intelligent systems work and emphasize the complementarity of solutions adopted to increase the safety, efficiency and adaptability of mechanized technologies in fruit growing.

Overall, the results obtained confirm the coherent and stable operation of the integrated intelligent systems on the three analyzed equipment, highlighting their ability to provide relevant information on mechanical loads, hydraulic conditions, operational stability and the dynamics of interaction with the working environment. Monitoring of functional parameters allowed the identification of the characteristic trends of each equipment and the way in which they influence the quality of fruit-growing works, demonstrating the usefulness of detection and control systems in optimizing adjustments and exploitation processes. Although the results are in the preliminary stage, the information obtained constitutes a solid basis for future calibration of the equipment and for the development of advanced evaluation models, which will allow a quantitative interpretation and a complete validation of the technological performances.

CONCLUSIONS

- The integration of intelligent systems into fruit growing technologies represents an important step in the transition towards sustainable agriculture with intelligent horticultural systems, in which decisions regarding the monitoring and regulation of equipment working parameters, the protection of working organs or the optimization of consumption are based on objective data.
- The analysis of intelligent monitoring systems integrated on equipment intended for mechanized technologies in fruit growing highlights the significant potential of digitalization on operational efficiency in this sector. The implementation of sensors and acquisition modules on ETR, ERI and PP has demonstrated that monitoring functional parameters can provide essential information on the technical behavior of equipment and can contribute to more precise adjustments, safer operation and work processes better adapted to field variability.
- Mechanized inflorescence thinning devices and sensor technology represent modern solutions for optimizing fruit production. The paper addresses current aspects regarding the development of inflorescence thinning technology in fruit trees, integrating innovations from the field of precision agriculture.
- The results obtained confirm the relevance of intelligent systems for increasing operator safety, by minimizing risks during platform movement and during works carried out at the crown level. - The data provided by the monitoring systems can be further exploited in predictive maintenance programs, in comparative analyses between technologies or in the substantiation of automated control algorithms.
- The integration of monitoring and control technologies into orchard maintenance equipment represents a strategic direction for the modernization of mechanization in orchards. Continuing this approach by expanding testing, quantitative validation of parameters and developing advanced predictive models will strengthen the position of these technologies as key elements of Agriculture 4.0 and will contribute to increasing the sustainability, competitiveness and performance of the orchard sector.

Acknowledgment

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WOOD–BASED WASTE RECYCLED INTO NEW ENGINEERED WOOD PRODUCTS IN A WASTE HIERARCHY CONCEPT – EXPANDED LITERATURE REVIEW

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DEȘEURI PE BAZĂ DE LEMN RECICLATE ÎN PRODUSE NOI DIN LEMN INGINERESC ÎN CONCEPTUL IERARHIEI DEȘEURILOR – CERCETARE EXTINSĂ A LITERATURII

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ABSTRACT

Wood–based waste products can be reused and recycled into new wood products by following a waste hierarchy that prioritizes reducing, reusing, and recycling before disposal. In the context of wood product manufacturing, the reuse of wood waste aligns with conserving resources, reducing landfill waste, and promoting circular economy principles. In fact, wood–based product manufacturing increasingly integrates wood waste recycling by converting post–consumer or post–industrial wood into new board products – panelboard manufacturing (particleboard, MDF) –, adhering to the waste hierarchy prioritizing reuse and recycling over disposal. Wood waste includes all wood and wood–based products at the end of their useful life, such as pallets, furniture, construction and demolition wood, and industrial and forestry residues. Recycling refers to processing wood waste into new products like particleboard, medium–density fiberboard (MDF), wood pellets for fuel, or mulch. It involves mechanical processing (shredding, grinding), removal of contaminants, and reforming into usable materials. Recycling extends wood fiber usage across multiple life cycles. The paper concludes with a comprehensive assessment of future pathways for circularity in the wood sector. This paper examines how wood–based waste can be transformed into new EWPs and evaluates the technological, environmental, and socio–economic implications. This paper reviews the state of the art in wood–waste recycling technologies, evaluates environmental and economic benefits, outlines methodologies and best practices, discusses emerging perspectives, and critically examines limitations.

REZUMAT

Produsele reziduale pe bază de lemn pot fi reutilizate și reciclate în produse noi din lemn, urmând o ierarhie a deșeurilor care prioritizează reducerea, reutilizarea și reciclarea înainte de eliminare. În contextul fabricării produselor din lemn, reutilizarea deșeurilor de lemn se aliniază cu conservarea resurselor, reducerea deșeurilor la groapa de gunoi și promovarea principiilor economiei circulare. De fapt, producția produselor pe bază de lemn integrează tot mai mult reciclarea deșeurilor de lemn prin transformarea lemnului post–consumator sau post–industrial în produse noi din panouri – fabricarea panourilor (paniol, MDF) –, respectând ierarhia deșeurilor care prioritizează reutilizarea și reciclarea în detrimentul eliminării. Deșeurile din lemn includ toate produsele din lemn aflate la sfârșitul duratei lor de viață utilă, cum ar fi paleții, mobilierul, lemnul de construcții și demolări, precum și reziduurile industriale și forestiere. Reciclarea se referă la procesarea deșeurilor de lemn în produse noi, cum ar fi panourile de particule, plăcile de fibră de densitate medie (MDF), peleții de lemn pentru combustibil sau mulci. Aceasta implică procesare mecanică (tocare, măcinare), îndepărtarea contaminanților și reformarea în materiale utilizabile. Reciclarea extinde utilizarea fibrelor de lemn pe mai multe cicluri de viață. Lucrarea se încheie cu o evaluare cuprinzătoare a căilor viitoare pentru circularitate în sectorul lemnului. Această lucrare analizează modul în care deșeurile pe bază de lemn pot fi transformate în noi EWP–uri și evaluează implicațiile tehnologice, de mediu și socio–economice. Această lucrare analizează stadiul tehnologiei în tehnologiile de reciclare a deșeurilor din lemn, evaluează beneficiile de mediu și economice, prezintă metodologii și cele mai bune practici, discută perspective emergente și analizează critic limitările.

INTRODUCTION

The global wood industry is undergoing a profound transformation driven by increasing material demand, resource scarcity, and the urgent need to reduce environmental impacts associated with construction and manufacturing. Wood–based waste—generated from construction and demolition (C&D), industrial processing, packaging, and post–consumer products—represents one of the largest waste streams in many industrialized regions. (*Kiesnere, G.et al, 2024; Oyenuga, A. A.et al, 2017; Besserer, A.et al, 2021; Goldhahn, C.et al, 2021*) Historically, a substantial portion of this waste has been landfilled or incinerated, often due to contamination, lack of sorting infrastructure, or limited market demand for recycled wood. However, the shift toward circular–economy principles has catalyzed renewed interest in recycling wood waste into high–value engineered wood products (EWPs).

Wood is one of the most widely used renewable materials, yet large volumes of wood waste are landfilled or incinerated despite their potential for high–value recycling. The waste–hierarchy concept—reduce, reuse, recycle, recover, dispose—provides a strategic framework for maximizing resource efficiency. Integrating wood–waste recycling into engineered wood product manufacturing supports circular–economy objectives, reduces pressure on forests, and lowers greenhouse–gas emissions.

The increasing generation of wood–based waste from construction, demolition, packaging, and industrial processing has intensified the need for sustainable material cycles. Recycling wood waste into engineered wood products (EWPs) aligns with the waste–hierarchy concept, which prioritizes prevention, reuse, and recycling over energy recovery and disposal. (*Kiesnere, G.et al, 2024; Ormondroyd, G. A.et al, 2016; Goldhahn, C.et al, 2021; Sandberg, D.et al, 2023*)

The waste–hierarchy concept, widely adopted in European and international waste policy, prioritizes PREVENTION, REUSE, and RECYCLING over ENERGY RECOVERY and DISPOSAL. Within this framework, recycling wood waste into EWPs is increasingly recognized as a strategic intervention that simultaneously reduces environmental burdens and enhances resource efficiency. Numerous studies have demonstrated that recycling wood waste can significantly reduce greenhouse–gas emissions compared to incineration, while also extending the carbon storage period by embedding carbon into long–life construction materials. (*Knauf, M., 2015; Awino, F.B. & Apitz, S.E., 2024; Farjana, S.H. & Ashraf, M., 2025; Singh, J. & Ordoñez, I., 2016*) This aligns with broader climate–mitigation strategies, particularly in the building sector, where material substitution and circularity are emerging as key levers for decarbonization.

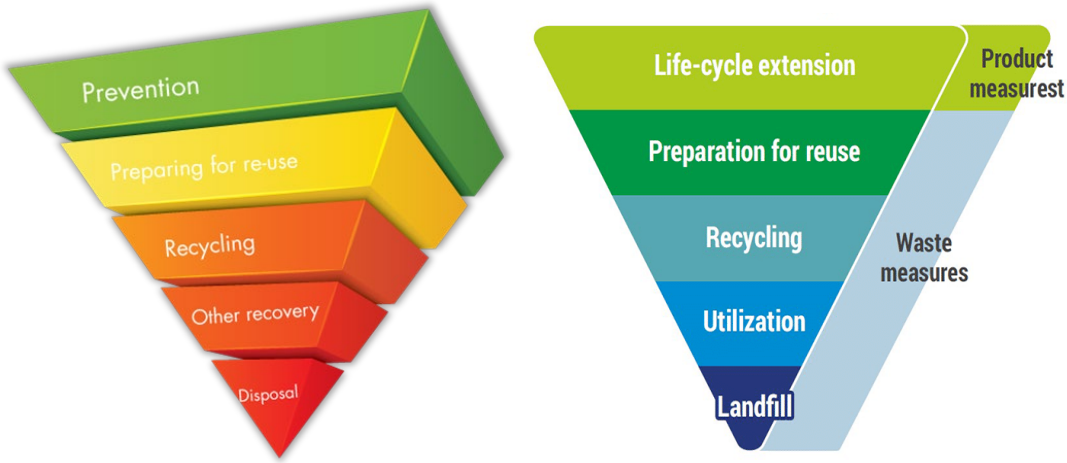

Fig. 1 – The waste–hierarchy concept

ENGINEERED WOOD PRODUCTS—such as particleboard, medium–density fiberboard (MDF), oriented strand board (OSB), laminated veneer lumber (LVL), glulam, and cross–laminated timber (CLT)—offer a versatile platform for integrating recycled wood fibers and particles. Particleboard and MDF have historically been the primary recipients of recycled wood, due to their tolerance for heterogeneous feedstock and the maturity of their manufacturing processes. (*de Carvalho Araújo, C. K., 2019; Maier, D., 2021; Van Ewijk, S.et al, 2016, Singh, J. & Ordoñez, I., 2016*) However, recent research has explored the feasibility of incorporating recycled wood into higher–performance structural products, driven by advances in sorting technologies, adhesive systems, and quality–control methods.

Despite these advancements, several challenges persist. Contamination—particularly from coatings, preservatives, metals, and composite materials—remains a major barrier to high–value recycling. Variability in feedstock quality complicates process optimization and can affect mechanical performance. Regulatory

frameworks, especially those governing hazardous substances, further restrict the use of certain waste–wood fractions. (*Maier, D., 2021; Psilovikos, T. A., 2023; Knauf, M., 2015*) These constraints highlight the need for improved sorting, decontamination, and characterization technologies, as well as harmonized standards that support the safe and effective use of recycled wood in EWPs.

Wood–based waste represents a significant and growing material stream generated from construction, demolition, industrial processing, and post–consumer use. Recycling this waste into engineered wood products (EWPs) aligns with the waste–hierarchy concept, which prioritizes prevention, reuse, and recycling over energy recovery and disposal. (*Kiesnere, G., 2024; Farjana, S. H. & Ashraf, M., 2025*)

Recycling wood–based waste into engineered wood products represents a critical strategy for advancing circularity in the construction and materials sectors. The waste–hierarchy concept provides a clear framework that prioritizes recycling over energy recovery and disposal, and current technologies demonstrate that high–quality EWPs can be produced from a wide range of waste–wood streams. The environmental benefits—including reduced carbon emissions, conservation of forest resources, and minimized landfill use—are substantial.(*Knauf, M., 2015*) Economically, recycled wood offers cost savings and new market opportunities, while socially it aligns with sustainability goals and regulatory trends.

Overall, the literature indicates a growing consensus that wood–waste recycling is both technically feasible and environmentally beneficial, but its full potential remains underutilized. Overall, the literature indicates a growing consensus that wood–waste recycling is both technically feasible and environmentally beneficial, but its full potential remains underutilized. (*Awino, F.B. & Apitz, S.E., 2024; Knauf, M., 2015*) The following section provides a detailed review of the state of the art in wood–waste recycling technologies, benefits, methodologies, criticisms, applications, future perspectives and emerging innovations.

STATE OF THE ART – EXPANDED LITERATURE REVIEW

SOURCES, CLASSIFICATION, AND CHARACTERISTICS OF WOOD WASTE

Wood waste arises from diverse sources including construction and demolition (C&D), manufacturing offcuts, pallets, furniture, and forestry residues, characterized by variability in moisture, contaminants, and degradation that impacts recycling into engineered wood products (EWPs). Construction generates 40–50% of wood waste via demolition timber, formwork, and cladding; manufacturing yields clean sawdust, shavings, and edge trims; while municipal streams include pallets, furniture, and garden waste like removed trees. Forestry byproducts and urban tree removals add untreated residues, with C&D often dominating mixed hazardous loads.(*Farjana, S. H. & Ashraf, M., 2025; Maier, D., 2021*)

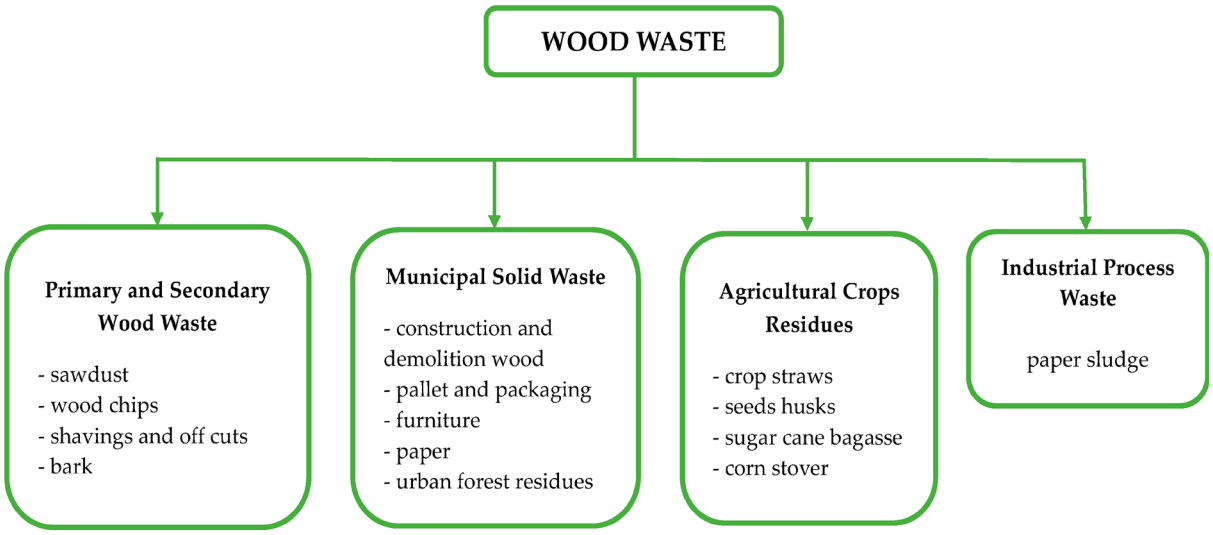

Fig. 2 – Classification of Wood Waste

Wood waste is typically categorized into several classes based on origin and contamination level. Construction and demolition waste (C&DW) is one of the largest contributors, comprising structural timber, formwork, flooring, and interior elements. This waste stream is often highly heterogeneous and may contain coatings, fasteners, adhesives, and chemical preservatives. Industrial wood waste—such as sawdust, shavings, veneer offcuts, and panel trimmings—is generally cleaner and more uniform, making it more suitable for high–quality recycling. (Bes*serer, A.et al, 2021; Goldhahn, C.et al, 2021; Singh, J. & Ordoñez, I.,*

2016; Awino, F. B. & Apitz, S. E., 2024) Post–consumer wood waste, including furniture and packaging, presents intermediate challenges, with variable contamination and composite materials.

- Construction and demolition represents the largest global source of wood waste, contributing 40–50% of volumes due to discarded framing, cladding, and demolition timber amid rapid urbanization.
- Sawmills, furniture production, and pallet manufacturing generate 20–30% of wood waste as clean offcuts, shavings, and edge trims, with high recyclability into EWPs.
- Municipal streams (10–20%) include pallets, furniture, and garden waste like tree removals, while forestry residues add untreated byproducts

Fig. 3 – Post–consumer wood waste from construction and demolition

Fig. 4 – Post–consumer wood waste from sawmills, furniture production, and pallet manufacturing

Fig. 5 – Post–consumer wood waste from municipal streams

Several classification systems have been developed to support recycling. European standards often distinguish between untreated wood, coated wood, and chemically treated wood, with only the first two categories typically eligible for material recycling. Studies have shown that contamination levels strongly influence the mechanical and chemical properties of recycled fibers, affecting their suitability for different EWP applications. (*Kiss, I.et al, 2025*) Classification systems—particularly in Europe—distinguish between untreated, coated, and chemically treated wood. Only the first two categories are typically eligible for material recycling. Contamination levels strongly influence mechanical and chemical properties, affecting suitability for different EWP applications.

Current literature and practice distinguish several categories of wood waste: clean, untreated wood (offcuts, pallets), coated but untreated wood (painted, laminated), and preservative–treated or heavily contaminated wood (construction and demolition wood with metals, gypsum, plastics, and chemical treatments). Modern classification schemes in Europe and elsewhere increasingly formalize these categories

to decide which fractions are suitable for material recycling into panels and which must be directed to energy recovery or specialized treatment. Frameworks for “wood waste valorization” emphasize the need for standardized classification and traceability to support higher–value recycling routes instead of defaulting to combustion or landfill. (*Awino, F. B., Apitz, S. E., 2024; Psilovikos, T. A., 2023; Maier, D., 2021*)

In parallel, the concept of “cascade use” has become central: wood is first used in long–lived structural elements, then in secondary products such as panels and furniture, followed by lower–grade uses (e.g., landscaping, animal bedding), and finally bioenergy. (*Besserer, A.et al, 2021; Psilovikos, T. A., 2023*) Reviews on cascading recycling of wood highlight that maximizing the number and duration of material cycles provides superior climate and resource benefits compared to single–use followed by combustion, provided that logistics, contamination control, and product performance are managed adequately.

Recycled wood has long been incorporated in particleboard, especially in core layers, while face layers still often rely on higher–quality virgin particles to ensure surface quality and machining performance. MDF and other fibreboards increasingly integrate recycled fibres, particularly from post–industrial waste such as trimming and sanding dust, though mechanical properties can degrade if fibre quality and bonding are not carefully controlled. (Kiss, I.et al, 2025) In OSB and structural panels, use of recycled strands is more limited due to strict mechanical and reliability requirements, but there is emerging work on hybrid boards where non–structural layers or components integrate recycled material.

ESTABLISHED RECYCLING PATHWAYS

Wood–based waste recycling into engineered wood products (EWPs) follows structured pathways emphasizing sorting, processing, and reintegration to promote circularity. (*Kiss, I.et al, 2025*)

- MECHANICAL RECYCLING PATHWAY: Waste wood undergoes sorting to separate untreated (clean) from treated or contaminated streams, followed by shredding, chipping, grinding, or milling into particles or fibers. These are then mixed with resins and hot–pressed into EWPs like particleboard, MDF, or OSB, with advanced sorting technologies enabling type–specific recycling (e.g., plywood to particleboard feedstock). Remediation removes contaminants like metals or paints beforehand to ensure quality.
- THERMAL AND CHEMICAL PATHWAYS: Lower–grade waste suits thermochemical routes: pyrolysis converts it to biochar or syngas for energy or hybrid EWP additives, while gasification produces fuel gases reducing fossil dependencies. Cascading uses remediated wood for composting or soil amendments post–energy recovery, extending utility beyond structural panels.
- INTEGRATED CASCADE FRAMEWORK: Pathways prioritize high–value mechanical reuse first, escalating to energy recovery or disposal only for residuals, as seen in LCA studies showing panel production outperforms landfilling by cutting emissions significantly. Processors compact and transport waste to facilities for consistent outputs like mulch, pellets, or biomass, supporting markets from construction to biofuels.

Established recycling pathways for wood–based waste into engineered wood products (EWPs) prioritize mechanical processing for high–value reuse, followed by thermal options for residuals:

- PARTICLEBOARD AND MDF PRODUCTION: Particleboard and MDF remain the dominant applications for recycled wood due to their ability to incorporate mixed particle sizes and fiber qualities. Research indicates that up to 30–60% recycled content can be used without significantly compromising mechanical performance, provided that contamination is adequately controlled. Several industrial plants in Europe already rely heavily on recycled wood, demonstrating the technical maturity of this pathway.
- WOOD–PLASTIC COMPOSITES (WPCs): WPCs represent another established application, particularly for outdoor decking, cladding, and automotive components. Recycled wood flour is commonly used as a filler, improving stiffness and reducing polymer consumption. Studies highlight that WPCs can tolerate higher levels of variability in wood feedstock, making them suitable for lower–grade waste fractions.
- BIO–BASED AND BINDER–FREE PANELS: Recent research has explored the use of natural adhesives—such as lignin, tannins, proteins, and starches—to produce bio–based panels with reduced formaldehyde emissions. Binder–free panels, produced through hot pressing of lignocellulosic fibers, rely on self–bonding mechanisms activated by heat and pressure. These innovations offer promising pathways for integrating recycled fibers into environmentally friendly products.

— STRUCTURAL ENGINEERED WOOD PRODUCTS: Although still in early development, several studies have investigated the use of recycled wood in structural EWPs such as CLT, LVL, and glulam. Reclaimed timber can be finger–jointed and laminated to produce structural elements, provided that defects and contaminants are removed. Research on recycled–content CLT panels suggests potential for non–load–bearing or secondary structural applications, though further testing is required to ensure compliance with building codes.

Recycling pathways for wood–based waste into engineered wood products (EWPs) define structured sequences of mechanical, thermal, or chemical processes that convert construction, demolition, or manufacturing residues into panels like particleboard, MDF, or OSB, prioritizing material circularity over disposal. (*Farjana, S.H.& Ashraf, M., 2025; Maier, D., 2021*) This dominant route starts with sorting clean from contaminated wood, followed by shredding, chipping, grinding, or milling into uniform particles or fibers, which mix with resins and press into EWPs; remediation removes paints or metals to ensure quality.

BENEFITS OF RECYCLING WOOD WASTE INTO ENGINEERED WOOD PRODUCTS

Recycling wood waste into engineered wood products (EWPs) yields environmental, economic, and social advantages by diverting landfill–bound materials into valuable panels like particleboard or MDF.

ENVIRONMENTAL BENEFITS

— REDUCTION OF VIRGIN TIMBER DEMAND: A substantial body of research highlights that substituting virgin wood with recycled wood particles or fibers can significantly reduce harvesting pressure on forests. Studies on material–flow analysis show that particleboard and MDF production are among the largest industrial consumers of small–diameter logs and sawmill residues. By integrating recycled wood, manufacturers can reduce reliance on primary resources, contributing to forest conservation and biodiversity protection.

— CLIMATE–CHANGE MITIGATION AND CARBON STORAGE: Wood products act as carbon sinks, storing biogenic carbon for the duration of their service life. Recycling wood waste into long–life EWPs extends this storage period, delaying carbon release that would otherwise occur through incineration or decomposition. Life–cycle assessment (LCA) studies consistently demonstrate that recycling yields lower global warming potential (GWP) compared to energy recovery, even when accounting for transportation and processing emissions.

— REDUCED LANDFILL BURDEN AND POLLUTION: Landfilled wood waste contributes to methane emissions, a potent greenhouse gas. Moreover, treated wood can leach hazardous substances into soil and groundwater. Recycling diverts material from landfills, reducing environmental risks and supporting national waste–reduction targets. Several countries have introduced landfill bans for recyclable wood fractions, reflecting the environmental advantages documented in the literature.

This process reduces deforestation by substituting virgin timber, cuts greenhouse gas emissions through lower energy demands versus primary production, and minimizes landfill methane releases. It promotes circularity, conserving resources and biodiversity while repurposing scraps into durable products.

ECONOMIC BENEFITS

— COST SAVINGS AND RESOURCE EFFICIENCY: Recycled wood is generally cheaper than virgin wood chips or fibers, especially in regions with high waste–collection efficiency. Economic analyses show that manufacturers can reduce raw–material costs by 10–40% depending on the proportion of recycled content and local waste–market conditions. This cost advantage is particularly relevant as global timber prices fluctuate due to supply constraints and geopolitical factors.

— MARKET EXPANSION AND INNOVATION: The growing demand for sustainable construction materials has created new market opportunities for recycled–content EWPs. Green–building certifications increasingly reward recycled content, stimulating innovation in product development. Companies that adopt circular practices often gain competitive advantages through branding, regulatory compliance, and access to eco–conscious consumer segments.

Job creation spans collection, processing, and manufacturing, lowering waste disposal costs and generating revenue from recycled EWPs sold as cost–effective alternatives to new wood. Markets expand for sustainable materials, fostering innovation in products like furniture or construction panels.

SOCIAL AND POLICY BENEFITS

— ALIGNMENT WITH CIRCULAR–ECONOMY POLICIES: The European Union's Circular Economy Action Plan and similar national frameworks emphasize material recovery and recycling. Wood–waste recycling directly supports these policy objectives, making it a priority area for research funding and industrial investment.

— JOB CREATION AND REGIONAL DEVELOPMENT: Recycling industries—particularly sorting, processing, and panel manufacturing—create skilled and semi–skilled jobs. Studies on regional economic development show that circular–economy sectors often stimulate local economies by creating stable employment and reducing dependence on imported raw materials.

Communities gain from reduced pollution, enhanced local economies, and increased awareness of sustainability, supporting resilient supply chains and eco–friendly construction practices. (*Kiss, I.et al, 2025*)

CRITICISM AND LIMITATIONS

Criticism of transforming wood–based waste into engineered wood products (EWPs) centers on overstated environmental benefits, persistent quality shortfalls, and systemic inefficiencies that undermine circularity claims. (*Kiss, I.et al, 2025*) Recycled EWPs often exhibit inferior mechanical properties due to degraded fibers from aged or weathered waste, leading to lower strength and durability compared to virgin–based panels, which critics argue justifies downcycling rather than true reuse.

TECHNICAL LIMITATIONS

Technical limitations in transforming wood–based waste into engineered wood products (EWPs) arise mainly from material variability, contamination issues, and processing inefficiencies that degrade final product quality. Key aspect are:

— Feedstock Variability: Waste wood is inherently heterogeneous. Variability in density, moisture, and contamination complicates process control and can lead to inconsistent product quality. Several studies highlight that variability is the single greatest barrier to scaling high–value recycling.

— Contamination Challenges: Preservatives such as CCA (chromated copper arsenate) and creosote pose significant risks. Even small amounts of contaminated wood can compromise entire batches of recycled material. Research on advanced detection technologies is ongoing, but no method is yet foolproof.

Heterogeneous waste features mixed species, biological damage, mechanical wear, and irregular geometries (e.g., wane or holes), hindering consistent grading and reprocessing into uniform fibers or particles for high–value EWPs. Energy–intensive grinding exacerbates issues, with aged wood showing reduced bonding efficiency compared to virgin fibers.

Lack of advanced sorting technologies for hazardous detection limits throughput, while reprocessing cross–sections alters essential properties, lacking standards for recertification in structural applications. Downcycling to low–grade products remains dominant due to these barriers over direct reuse.

ECONOMIC AND MARKET BARRIERS

Economic and market barriers hinder the transformation of wood–based waste into engineered wood products (EWPs), primarily due to cost disparities and supply chain inefficiencies that favor virgin materials. High labor and processing costs for sorting, shredding, and remediating contaminated waste exceed the low prices of virgin wood, making recycling uneconomical despite environmental gains; for instance, MDF recovery often fails viability tests due to specialized infrastructure needs. Key aspect are:

— High Sorting and Cleaning Costs: Automated sorting technologies require substantial capital investment. In regions with low landfill fees or abundant virgin timber, recycling may not be economically competitive.

— Market Perception: Some consumers and manufacturers perceive recycled wood as inferior. Studies on consumer behavior suggest that certification schemes and transparent labeling can help overcome this barrier.

Logistical challenges, including fragmented collection from construction sites and lack of unified markets, exacerbate supply shortages, with reclaimed wood comprising minimal feedstock shares. Limited vertical integration from waste to finished EWPs reduces value capture, stalling industry adoption.

REGULATORY CONSTRAINTS

Regulatory constraints on transforming wood–based waste into engineered wood products (EWPs) primarily stem from waste classification systems, contamination controls, and emissions standards that vary by region, often prioritizing safety over circularity. (*Kiss, I.et al, 2025*) These frameworks boost safety but raise costs, hindering small–scale EWP adoption. Key aspects are:

— Hazardous–Substance Regulations: Strict regulations on hazardous substances limit the use of certain waste–wood fractions. While necessary for safety, these regulations can reduce recycling rates.

— Lack of Standards for Structural Recycled Products: There is currently no harmonized standard for structural EWPs containing recycled wood. This regulatory gap restricts market adoption.

Overall, pathways favour low–value outputs like mulch over high–grade EWPs, perpetuating linear waste flows. (*Kiss, I.et al, 2025*)

DISCUSSION

Recycling wood–based waste into new engineered wood products within a waste–hierarchy framework represents a central strategy for advancing the circular bioeconomy of the forestry and construction sectors. (*Kiss, I.et al, 2025*) When implemented with robust quality control, effective contamination management, and optimized logistics, such recycling can reduce reliance on virgin timber, extend carbon storage in long–lived materials, and substantially cut landfill volumes and associated greenhouse gas emissions. At the same time, it supports industrial symbiosis and generates local economic benefits in collection, recycling, and manufacturing.

Technological progress over the last decades has consolidated the use of recycled wood in particleboard, and increasingly in other panel and composite products. Improved sorting, sensor–based classification, and mechanical pre–treatments have made it possible to integrate diverse waste streams while maintaining or even enhancing performance in non–structural applications. Methodologies incorporating LCA and techno–economic analysis have begun to guide product development, helping to identify where recycled content maximizes environmental benefits without compromising functional performance or safety. Yet, this integration is far from complete, and many promising innovations remain at pilot or early industrial stage.

Looking forward, the most promising trajectory combines three elements. First, upstream interventions such as design for disassembly and material passports should reduce contamination and improve traceability, ensuring that future wood waste emerges as a high–quality secondary resource rather than a problematic mixed stream. Second, mid–stream innovation in adhesives, hybrid panel design, and thermochemical pre–treatments should expand the range of EWPs capable of incorporating high–recycled content, including in semi–structural or structural roles under defined conditions. Third, downstream governance instruments—standards, regulations, and market incentives—must be calibrated to reward safe, high–value recycling while preserving the primacy of waste prevention and reuse.

Nevertheless, structural limitations and trade–offs must be recognized. Not all wood waste can or should be recycled into panels; highly contaminated fractions may be more appropriately treated through energy recovery or specialized remediation. Even for cleaner streams, transportation distances, required processing energy, and the need for higher resin contents can erode some of the environmental advantages of recycling. There is also the risk that focusing on recycling diverts attention from systemic changes, such as reducing over–consumption of short–lived products, optimizing building lifetimes, and designing modular systems that can be reused with minimal transformation.

For researchers, important open questions include: quantifying the optimal balance between multiple cascade cycles and timely energy recovery under different regional energy mixes; developing adhesives and surface treatments fully compatible with repeated recycling while minimizing hazardous emissions; and designing EWPs that are robust to feedstock variability yet meet demanding performance standards. For industry and policy makers, priorities include establishing harmonized classification and quality standards for recycled wood, investing in high–efficiency sorting and cleaning technologies, and mainstreaming LCA–based decision tools in product and policy design.

In essence, recycling wood–based waste into engineered wood products has already moved from niche practice to an essential component of sustainable wood resource management and circular–economy strategies. Its future contribution will depend on integrating technological innovation with upstream design changes and supportive policy frameworks, while acknowledging and managing its limitations. (*Ormondroyd, G. A.et al, 2016; Goldhahn, C.et al 2021*) A nuanced application of the waste hierarchy—one that genuinely prioritizes prevention and reuse, but also unlocks the full potential of high–value recycling where appropriate—offers the most coherent pathway for maximizing the environmental, economic, and social benefits of wood in a resource–constrained, climate–challenged world. Several technological trends are expected to enhance the role of recycled wood in EWPs within the waste–hierarchy context:

— More sophisticated sensor–based sorting assisted classification will improve separation of clean recyclable wood from contaminated fractions, thus enabling higher–value applications.
— New adhesive systems, including formaldehyde–free and bio–based resins, are being tailored to work effectively with recycled particles and fibres, potentially tolerating more variability and extractives.

— Engineered hybrid systems (e.g., layered panels combining recycled wood cores with high–performance veneers, thin LVL, or fibre–reinforced skins) may unlock structural applications while relying heavily on recycled content in non–critical layers.
— Policy frameworks supporting waste hierarchy and circular economy, including landfill restrictions, extended producer responsibility (EPR) schemes, and public–procurement rules favoring recycled content, are expected to further stimulate wood–recycling markets. Harmonized classification and quality standards for recycled wood across regions would reduce uncertainty, lower transaction costs, and facilitate cross–border trade in secondary raw materials.

However, regulators face the challenge of balancing human–health and environmental protection (e.g., strict limits on hazardous substances in recycled panels) with the need to maximize safe material recycling. This balance may drive the adoption of risk–based approaches, where specific use contexts (e.g., non–residential, non–interior applications) allow somewhat higher tolerance for certain contaminants, provided that exposure pathways are controlled. From a critical viewpoint, there is also the risk that "recycling" is used rhetorically to justify otherwise unsustainable construction practices, where short–lived products generate large amounts of waste that are only partially valorized. The waste hierarchy reminds that prevention, reduction, and reuse should remain priorities over recycling, even when sophisticated recycling technologies are available.

CONCLUSIONS

This paper provides an extensive literature–based review of the state of the art in wood–waste recycling, including environmental and economic benefits, technological methodologies, operational practices, emerging innovations, and critical limitations. The analysis demonstrates that recycled wood can be successfully integrated into particleboard, fiberboard, wood–plastic composites, and even structural engineered products under certain conditions. However, challenges related to contamination, feedstock variability, regulatory constraints, and market acceptance remain significant. The paper concludes with a comprehensive assessment of future pathways for advancing circularity in the wood sector.

The literature overwhelmingly supports the environmental, economic, and social benefits of recycling wood waste into engineered wood products. The waste–hierarchy framework provides a strong conceptual foundation, emphasizing recycling as a preferred option over energy recovery and disposal. Technological advancements—particularly in sorting, decontamination, and adhesive systems—have significantly improved the feasibility of high–value recycling.

The recycling of wood–based waste into new–engineered wood products (EWPs) is a pivotal strategy within the waste hierarchy framework and the circular economy (CE) paradigm. It emphasizes maximizing resource efficiency, reducing landfill use, and promoting product life extension by transforming timber residues from construction, demolition, and industrial sources into value–added products like particleboard, medium–density fiberboard (MDF), and oriented strand board (OSB). Recycling wood–based waste into engineered wood products is an effective waste management strategy aligning with circular economy and waste hierarchy goals. It offers significant environmental advantages, supports resource conservation, and meets growing market demands for sustainable materials. Continued innovation, policy support, and infrastructure development are critical to overcoming current challenges and maximizing this sector's potential for carbon footprint reduction and circularity.

However, challenges remain. Feedstock variability, contamination, and regulatory constraints continue to limit the full integration of recycled wood into high–performance applications. Economic barriers, including high sorting costs and market skepticism, further complicate adoption. Addressing these challenges will require coordinated efforts across industry, academia, and policy sectors.

Particleboard and MDF remain the dominant applications for recycled wood due to their ability to incorporate mixed particle sizes and fiber qualities. Studies show that up to 30–60% recycled content can be used without significantly compromising mechanical performance, provided contamination is controlled. Several industrial plants already rely heavily on recycled wood.

WPCs use recycled wood flour as a filler, improving stiffness and reducing polymer consumption. They tolerate higher feedstock variability, making them suitable for lower–grade waste fractions. Future research should focus on:

— Developing robust quality–assessment protocols
— Advancing bio–based adhesives compatible with recycled fibers
— Creating standards for structural recycled–content EWPs

— Enhancing digital traceability through material passports
— Conducting long–term durability studies

Ultimately, the transition to a circular wood economy depends on systemic innovation and collaboration. With continued investment and policy support, recycled wood–based engineered products can play a central role in sustainable construction, resource conservation, and climate–change mitigation. The potential is substantial, and the momentum is growing.

Looking forward, the transition toward a circular wood economy will depend on innovation, standardization, and systemic thinking. With continued research and investment, recycled wood–based engineered products can become a mainstream solution, contributing significantly to sustainable construction and resource efficiency. The potential is clear: wood waste is not an endpoint but a valuable resource capable of re–entering the material cycle and supporting a more resilient, low–carbon future.

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STUDY ON BIOCHAR APPLICATION METHODOLOGIES IN DIFFERENT VEGETABLE CROPS- REVIEW/
STUDIU PRIVIND METODOLOGIILE DE APLICARE BIOCHAR IN DIFERITE CULTURI AGRICOLE LEGUMICOLE

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***Keywords: b**iochar applications, testing methodologies, crop biochar productivity, crop stimulation, vegetable production, plant healthy, greenhouse conditions.*

ABSTRACT
A synthesis of the methodologies for applying biochar to various vegetable crops is important because the results obtained from other research-development programs may be relevant for new studies in the field, and can serve as a guide for new research and, where necessary, can be improved, avoiding irrelevant or unproductive situations. Based on these, additional research can be carried out in the field, which may lead to the validation and performance enhancement of experimental vegetable crops to which biochar has been applied. Large-scale testing of this natural slow-release fertilizer (SRF), applied under similar or diverse conditions, leads to create and holistic or a dedicated agricultural–horticultural best-practice methodologies for administering biochar to seedlings or crops in fields and in protected environments (greenhouses, laboratories, nurseries, seedbeds, etc.). The most commonly studied crops are tomato, bell pepper, lettuce, and potato, therefore, this article presents a synthesis of the methodologies applied and the results obtained, thus outlining an appropriate technology for administering SRF to seedlings and crops in order to increase yield and efficiency, as well as to reduce production costs. By addressing this research, we offer farmers in the organic and biological food industry an alternative for stimulating productivity, aligned with the concept of sustainable, circular, and ecological agriculture.

REZUMAT
O sinteza a metodologiilor de aplicare bio-cărbune pentru diferite culturi legumicole este importantă deoarece rezultatele obținute din alte programe de cercetare-dezvoltare, pot fi relevante pentru noile cercetări in domeniu, si se pot considera ca un ghid pentru noile cercetări si unde este necesar se pot îmbunătății, evitând situațiile nerelevante/neproductive. Pe baza acestora se pot realiza alte cercetări in domeniu ce pot conduce la validarea si creșterea performantele culturilor legumicole experimentale in care au fost administrate bio-cărbune. Experimentarea pe scara larga a acestui îngrășământ natural lenți (SRF) administrat in aceleași sau in diverse condiții, conduc la crearea unor metodologii agricole-legumicole de bune practicii de administrare a bio-cărbunelui pentru răsadurile sau culturile din câmpuri sau din mediile protejate (sere, laboratoare, pepiniere, răsadnițe, etc.). Cele mai populare culturi sunt: roșie, ardei gras, salata verde si cartof, de aceea in acest articol se va prezenta o sinteza despre mitologiile aplicate și rezultatele obținute, astfel se conturează o tehnologie corectă de administrare a SFL pentru răsaduri și culturi pentru a creste producția si eficiența, precum și scăderea costurilor de producție. Prin abordarea acestor cercetări, oferim fermierilor din sectorul industriei alimentare ecologice si biologice o alternativă pentru stimularea productivității, care se alienează conceptului de agricultura sustenabilă, recirculară si ecologică.

INTRODUCTION

Agriculture researchers, chemists, agronomists, and land improvement specialists are working together to conserve and improve soil nutritional value, especially for those areas where it is used for intensive agriculture and carbon sequestration is essential. Until now, the biochar-based SRFs and nano SRFs field of application is limited, more than the biochar capitalization technology on open field is influenced by: soil composition, humidity, environmental conditions, and soil microorganism evolution (fungi, molds, bacteria, worms / earthworms, etc.), and the results obtained so far are not yet relevant. (*Jatuwong K. at al. 2025).* For this reason, it is appropriate to begin research in protected environments (controlled microclimate such as humidity, sunlight exposure, and controlled nutrient substrate), implanting a special microclimate condition specific to an area that will implement those results in open field conditions or large

scale. But, until now, the most practical and relevant application research results have been obtained in greenhouse conditions for vegetable crop production. (Jabborova D. et al., 2021) by applying 2 and 3% of commercial biochar to the soil, researchers improved the lettuce yield. Others found that the biochar obtained from poultry litter amendments promoted increased cultivation productivity. (Faria W.M. et al., 2018; De Lima W.B. et al., 2019) In other cases was added to soil 5, 10, and 15% of almond biochar and found that the lowest ratio of biochar presented better results in arugula seedlings (Sánchez, E. et al., 2022).

In some particular research activities, were conducted an analysis of bacterial and fungi evolution into a controlled contamination environment (nutritional substrate combined with SRF layer, with several concentrations) that is usually identified in natural production environments and has a positive impact on nutritional solution availability for some vegetable crops. (*Jatuwong K. et al., 2025*)

Taking a wide overview of this subsect, the biochar is a subproduct of many wastes, but the most indicated in agriculture is obtained from biomass or manure slow pyrolysis, so its administration is usually regulated by fertilizers or soil amendment administration national guides. But this subject is worldwide studied and analysed because its prevalence depends on biochar composition and its source. So, in order to be efficiently used in agriculture are made some mixtures (biomass and livestock manure; biomass and poultry droppings, biomass and dozens of pigs, biomass and food waste) are made that are tested (*Enders, A. et al., 2012; Conz, R.F. et al., 2017*) mainly for azoth-phosphor-potassium (NPK) elements.

The international biochar standards mention that the biochar quality is direct related with production costs and environmental impact, because they have a complex composition and have direct contact with all environmental factors (water, wind and soil), and if this soil improvement technology do not take in to consideration these factors, sometimes the desired effect is not achieved, or it can deteriorate it (contamination, salinity, erosion, swamp, etc.). (*Fernandes J.D et al, 2019; Enders a., Lehman J. in 2012*) So, the first step is to make a detailed biochar composition analyse: pH, electrical conductivity (EC); cation exchange capacity (CEC); proximate and elemental analysis, volatile matter [%], fixed carbon [%], ash [%], limits for organic contaminants; heavy metals, salt, granulation, etc.; and after that, is indicated to realise a quality certification (that can look like WBC form). In some papers is mentioned the evaluated in relation to their devolatilization characteristics, through thermogravimetry analysis, especially for feedstock samples (*Conz R.F. et al., 2017*).

Another important factor that is influencing the biochar efficiency is the soil composition/planting layer, so is ned to be done a similar soil composition analysis, that be conducted to establish an efficiency dosing strategy in accordance with agronomic crop necessity. Nower days, the spring/source/rain water composition analyse is also necessary, to increase the fertilizer efficiency and in this way can be made a crop dedicated fertilizer strategies for every developing stage. So personalized fertiliser technologies and mythologies are internationally encouraged, and the fertilizer production companies are launching a new strategy, the dedicated fertilizers production form large farmers and associations, so this tendency is a much customer strategy, and in some cases these companies work with banks to grant attractive loans for these works, and not to name.

A holistic approach is necessary for field research conditions, because it is necessary to overcome the unforeseen climate changes and environmental response to them, situations that were documented in some research papers. So, to simplify the vegetable research approach were conducted semi-protected/ protected environmental crop studies. In the first case, the seedlings are grown in greenhouses and then are planted in gardens or semi-open greenhouses. The second case implies the plug tray seedling, then replicate them in a seedling house, and finally, in greenhouse conditions. In this paper will be studied these situations and the vegetable crop productivity (tomato, bell peppers, lettuce, potato) in accordance with biochar rate of administration, research that is relevant for greenhouse or semi-open vegetables crops farmers, and also for seedling production agents (horticulture, forestry, stone fruits seedlings, etc).

MATERIALS AND METHODS

In order to analyse biochar administration methodology is essential to have a large picture image, and to understand the biochar influence (NPK elements) upon the soil and plant growing and productivity is usually established a nutritive substance balance and its distributions for each evolutionary stage and plant part are established, as is presented in Fig.1. (*Madjar R. and Davidescu V.,2009*) Also, the biochar generally has important mineral contents, making it a promising biofertilizer due to its positive influence on the germination, growth, and development of cultivations. (*Senbayram, M. et al.,2019; Kamali M., et al., 2022*).

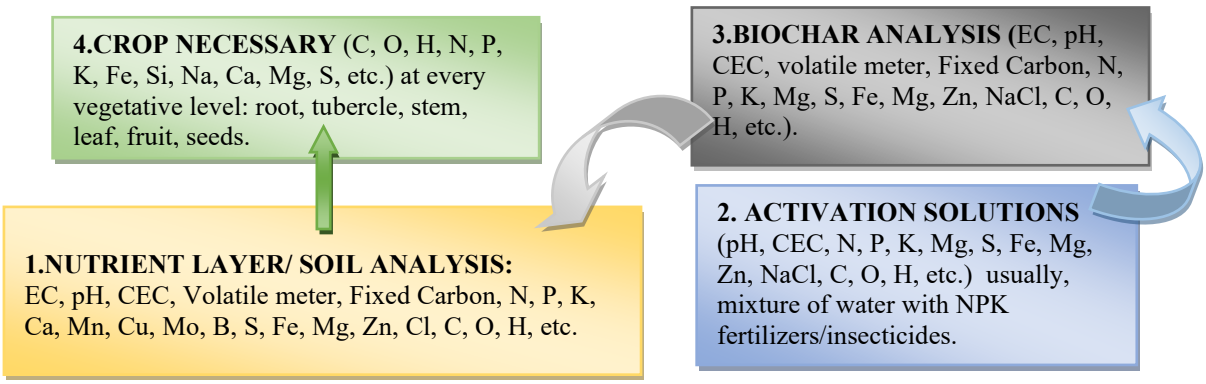

Fig. 1. Fito-nutrient substance analyse flow.

Usually, the biochar application technology, as an SRF mentions the activation solutions (*Susaimanickam A, et al., 2021; Sakhiya A.K. and Anand A., 2020; Bryan Díaz B. Et al., 2024; V. U. Bambhaniya V.U. et al, 2025*), which is a process to add some additional properties in cases in which the biochar quality does not comply with the vegetable crop necessary when it is applied on nutrient layers during the germination/replication/planting development stage (plant requirements in species-variety-age).

In some researches where examined the effects of cow manure, poultry manure, and vermicompost, in combination with inorganic fertilizers, on the growth and yield of C. annuum. Analyzing the results, revealed enhancements in pepper growth and yield, along with greater nutrient uptake compared to chemical fertilization alone. Vermicompost emerged as the most effective alternative for enhancing pepper production. Exploring further, the effects of fertigation on the soil chemical properties of peppers, the Poliquit D., et al, 2022, investigated various treatments, including water-soluble fertilizer, commercial controlled-release fertilizer, and fert-irrigation in different ratios. Their findings demonstrated a significant **improvement** in soil characteristics such as pH, OM, nitrogen (N), phosphorus (P), and potassium (K) contents. Furthermore, they observed that nitrogen (N), phosphorus (P_2O_5), and potassium (K_2O) levels correlated with increased pepper yield.

Another delicate subject, with very great importance, is water analysis before mixt the additional solutions or soluble powders, so the NPK mineral nutrition of the plant to be stimulated and to avoid the nutritive unbalance (without ions susceptible to accumulate in the soil), case when is applied to much fertilizer dosage (ammonium nitrate, urea, calcium nitrate, ammonium phosphate and potassium nitrate).

The biochar granulation is justified if it's considered insoluble fertilizers and their particular granulation must be within 3 ÷ 5 mm in diameter (if it's much greater than 5 mm is not admissible because it leads to a high concentration of nutrients, especially for germination and growing). Its application rate is: between 5 ÷ 10 kg/m^3 for organic layer in nutritive pots; and between 0.5 ÷ 1.5 at vegetable seedlings. (*Madjar R. and Davidescu V., 2009*).

Several case studies regarding for vegetable type crop productions (fruit crop- tomato; shell fruit crop – paper; leaf crop – lettuce; tubercule crop – potato) are structed order to see the main methodology stapes and materials used to increase crop yield on which is applied several biochar types.

1. **The tomato crop (***Solanum lycopersicum L.)* is one of the most important crops cultivated in Uganda for its economic, nutritional and health promoting benefits. (*Wacal C., et al., 2023; Jatuwong K., et al., 2025*). The fruits are rich in vitamins, minerals, fibber, protein, essential amino acids, monounsaturated fatty acids, carotenoids and phytosterols (*Elbadrawy E. and Sello, 2016; Ramos-Bueno R.P. at al.,2017; Chaudhary P. et al. 2018; Nasir M.U. et al. 2015*). In addition, lycopene is an important carotenoid found in tomatoes which possess antioxidant, anti-hypolipidemic, anticarcinogenic activities, and prevents cardiovascular diseases, while promoting cognitive function and preventing osteoporosis (*Ghadage S.R. et al., 2019; Ali M.Y. et al., 2021).* Because of these nutritional and health benefits, the demand and consumption of tomatoes is very high.

1.1. Tests conducted in field conditions at the University farm of Uganda Martyrs University, Ngetta Campus Lira, 2.31 30° N, 32.92 88° E.**,** where dominant soil at this site was classified as Plinthosol accordingly with FAO from 2012.

1.2. The climate conditions during the first (March–May) and second (June–September) rainfall seasons of 2022. Normally in field conditions, is necessary to make a journal with rainfall period, quantities and temperatures, and after that are corelated with crop vegetative stage. Following this strategy were noted,

one peak during April–May and the other in August-October. The first season had started in March until May (period with short rainfall), while between July and November were taken place long rainfall. Average annual rainfall received during the growing seasons and their peaks occurred in April (198.7 mm), May (173.6 mm), while highest rainfall was received in August (213.2 mm), followed by October (194.8 mm). While the average temperatures in the first and second seasons were 24.2^{0}C and 23.5^{0}C.

1.3. Biochar type and administration. In this, case had been adopted in-situ field method of maise biochar preparation in which a soil pyrolizer (also called a cuboid ditch or open pit method) was employed. biochar was crushed into powder and passed through a 2-mm sieve prior to determination of its properties. All chemical analysis were performed following the standards described by Okalebo et al., 2002*. (Wacal C. et al., 2023)* The ash content was measured by igniting 1.0 g biochar sample at 550 °C for 5 hours in a muffle furnace and ash content determined using the following.

1.4. Soil preparation the experiment was conducted on a field, measuring 10 m x 5 m divided into micro plots measuring 1 m x 1 m (1 m^2). The chemical properties of the soil were evaluated before and after the experiment were taken and centralised in table format (pH, EC, Total carbon, N, P, K, Ca, Mg, sand, clay, silt, texture, etc). Each micro plot was separated by 1 m as buffer space. Planting holes were made at spacing of 60 cm × 45 cm into which maize stover biochar was applied at varying rates (spot application method), respectively 0, 3.5 (1%), 6.9 (2%), 13.8 (4%) and 27.6 t/ha (8%), were arranged in completely randomized block design (CRBD) with three replicates. Only the control (0 t/ha) received the recommended basal inorganic fertilizer applied at a rate 185 kg/ha of diammonium phosphate (N—P_2O_5—K_2O, 18:46:0) which supplied 33 kg N/ ha and 85 kg P_2O_5/ha, while 48 kg N/ha was obtained from calcium ammonium nitrate (26% N) applied as top dressing.

1.5. The tomato seedlings. Tomato variety “Padma F1” was first raised in a nursery bed and after three (3) weeks, were transplanted directly in the holes in which inorganic fertilizer and biochar were incorporated following the spacing of 600 mm × 450 mm (37,037 plants/ha).

1.6. Crop management. The plants were supported keeping the foliage off the ground. The plots were weed free by regular hand weeding while pests and diseases were managed using recommended chemicals. The second cropping was conducted on the residual biochar on the same treatments without disturbing the plots during the second season. However, the control received the recommended inorganic fertilizer. All agronomic practices were followed as in the first season.

1.7. Methodology to assess the agronomic crop parameters during the cultivation cycle.

All data on growth and yield analysis were determined at harvest time. Parameters determined included: plant height, root weight (g), shoot weight (g), number of fruits per plant, fruit weight per plant grand fruit yield (t/ha). After harvest of the second season, soil samples were collected with an auger to a depth of 150 mm. The soil samples were air-dried, crushed, and passed through a 2 mm sieve and all chemical analyses were performed following standard methods described by Okalebo et al. After that, were analysed using a one-way analysis of variance (ANOVA) to examine the effect of biochar on soil chemical properties, growth and yield of tomatoes, using SPSS 20.0 software package (SPSS IncChicago, IL, USA); pairs of means were compared on significant ANOVA tests using Tukey’s honestly significant difference (HSD) test ($p < 0.05$). Unless otherwise noted, differences were considered significant at $p < 0.05$. The results were presented as the mean ± SE (standard errors) of the three replicates.

2. The green bell pepper (*Capsicum annuum L.*) crops represent the third most important crop in the world, a vegetable native to South and Central America, which has emerged as one of the three most grown commercial vegetables globally (*Sanchez E. et al., 2024).* In this case, wase used *pistachio shell-based biochar (PSB)* to improve soil drainage and plant availability (*Miri F., et asl, 2020).*

` **2.1 Tests conducted in greenhouse conditions,** town of Médano de Oro, Department of Rawson, Province of San Juan, Argentina. The greenhouse structure was strategically positioned with a west-east orientation, optimizing sunlight exposure to enhance plant growth and development (temperature and light parameters).

2.2 The climate is desert, with annual rainfall not exceeding 150 mm, concentrated in the summer period. The average annual temperature is 17.8 °C, and the average of the warmest month (January) is 26.3 °C.

2.3 Biochar type administered was obtained from 450 ^{0}C pyrolyzes, due to its quality (OM degradation was minimized) and its capacity to retain nutrients and water, thereby benefiting both soil health and plant growth (an optimal equilibrium it is necessary to obtain between OM retention and stable OC formation) which is a very important aspect for the long-term resilience of biochar in the soil. So, cost-

efficient factor is also taken into consideration, better results at a low energy consumption and production time (considering higher temperatures). The PSB granulation was set between 2 and 5 mm, and was uniformly integrated into the soil with a rake at depths ranging from 250 to 300 cm.

2.4 Soil preparation included flood irrigation followed by fluffing and weeding. In addition, the soil was fertilized with horse manure at a rate of 10,000 kg/ha. Three treatments were applied, differentiated by the PSB ratio (g/g) incorporated into the soil: SB0 (soil + 0% biochar, equivalent to 0 tons/ha); SB1 (soil + 1% biochar, equivalent to 10 tons/ha) and SB2 (soil + 2% biochar, equivalent to 20 tons/ha). Subsequently, the beds were prepared for transplanting the final cultivation, each with 25 plants. 10 samples were extracted at depths of 15 and 30 cm (the depths where roots branch out and where biological processes occur). Each sample weighs approximately 1 kg. Samples are taken before planting and after the crop is removed (to determine the physical-chemical properties balance) at depths of 250 ÷ 300 mm at the end of the vegetative cycle. After that, samples are dried and ground to 2 mm.

2.5 The green bell pepper seedlings of the Chango cultivar were obtained 50 days after germination with an average height of 60 mm and between 4 and 5 defined leaves. The plots were carefully delineated in furrows 0.7 m wide and spaced at regular intervals of 1.2 m. At the transplanting stage, the green bell pepper seedlings were obtained after 50 days from germination, having a height of 6 cm and 4÷5 rows of well-defined leaves. The manual transplanting process had taken place after three days after the soil was prepared, using transplanting cones to facilitate this work. The plating strategy was made according to a preestablished staggered frame with a 300 mm distance in any direction.

2.6 Crop management. The irrigation was made on two lines of billon, with a 3 ÷ 4 days frequency during cultivation. The manual weeding was carried out every 15 days. No pests or diseases were observed during the experiment, so no insecticide application was necessary. The crop was fertilized by direct injection into the irrigation system (fertigation) with a nitrogen product, without the need for prior dilution. No pruning, thinning, or other green work was carried out on the cultivation of bell pepper during its development. Finally, the fruits of the crop were harvested 120 days after transplantation.

2.7 Methodology to assess the agronomic crop parameters during the cultivation cycle

Measurements of plant height and number of leaves were made on 10 randomly selected plants during the phenological stages of the crop (vegetative - stage 1, reproductive - stage 2, and ripening - stage 3) for all treatments. Flowering plants and fruits were randomly counted for all treatments. The chlorophyll content (SPAD, index of chlorophyll content per unit leaf area) was determined with a portable chlorophyll meter (CM-B, Biobased, Jinan, China). Also, the influence on fruit morphological characteristics was analysed at the end of the growing cycle, fruits were randomly harvested for each treatment, and images were taken and processed to analysed the main morphological characteristics of the fruits, including average weight (g), length (cm), width (cm), wall thickness (mm), and total yield of green bell pepper (ton/ha). The pH (AOAC 10.042), moisture content (AOAC 925.10), acidity (AOAC 942.15), and soluble solids (AOAC 923.12) of the green bell pepper fruit were determined and placed on a table with physio-chemical parameters measured in fresh bell papers (average weight, length, with, wall thickness, pH, acidity, moisture content, soluble solids, fruit yield). The fruits evaluated were at the ripe green stage using AOAC from 2021.

3. Lettuce crop preparation and plant growing strategy

This study was conducted to fill the gap between the optimal production conditions and appropriate application rates of biochar derived from greenhouse crop by-products in South Korea, and its efficiency to be used in sustainable agricultural practices (*Lee Y.N. et al., 2024*) and circular agriculture. The short productivity crop is the lettuce crop and this fact is because of vegetative development stages (green leaf crop with no steam and fruits, and a small and light roots structure), so from seeds grow directly leaves and the crop management and assessment process is simpler and shorter.

3.1. Tests conducted in greenhouse conditions.

3.3 Biochar type and its application rate. Greenhouse crop residues (red pepper stalks) were collected from local area (Wanju, South korea). The residues were dried at 60 °C before pyrolysis process. The dried samples were placed in porcelain crucibles and were pyrolyzed for 2 h at various temperature conditions (200, 300, 400 and 600 °C) in furnace (DK-1015, STI tech, Gumi, South Korea), into which nitrogen gas was continuously injected to maintain the oxygen-limited conditions. The treatments included a control (no fertilizer- NF), an inorganic fertilizer (NPK fertilizer) and combined treatments of biochar with inorganic fertilizer (NPK + PB) at different application rates (100, 200, 400, 800, 1000 and 2000 kg per 10acres/areas) within ammoniac fertilizes (NPK+PB). Fertilizer application rates were based on the standard

recommendations for lettuce by the Rural Development Administration (N-P_2O5-K_2O = 10.0-5.9-12.8 kg per 10acre/areas). Those dosages were incorporated in the soil at a depth of 0 ÷ 150 mm.

3.4 Soil preparation and cultivation method. Basal fertilizer (N-P_2O5-K_2O = 7.0-3.0-3.6 kg per 10acre/areas) was applied one week before transplanting, and top-dressing (N-P_2O5-K_2O = 3.5-3.0-1.8 kg per 10acre/areas) was split into two applications at 15-day intervals, starting three weeks post-transplanting

Lettuce (Lactuca sativa L.) was chosen as the test crop, and lettuce were grown in the pot (1 5000/a). Biochar was applied at six levels (100, 200, 400, 800, 1,000, and 2,000 kg per 10acre/areas) and evenly incorporated into the topsoil at a depth of 0–15 cm. The treatments included a control (no fertilizer, NF), an inorganic fertilizer (NPK fertilizer, NPK), and combined treatments of biochar with inorganic

3.5 Crop management. Basal fertilizer (N-P_2O5-K_2O = 7.0-3.0-3.6 kg per 10acre/area) was applied one week before transplanting, and top-dressing (N-P_2O5-K_2O = 3.5-3.0-1.8 kg per 10acre/area) was split into two applications at 15-day intervals, starting three weeks post-transplanting

3.7 Methodology to assess the agronomic crop parameters during the cultivation cycle.

Soil chemical properties before and after crop cultivation were analysed according to the Rural Development Administration's Soil and Plant Analysis Methods, NIAS from 2000. To observe crop growth characteristics relative to biochar application rates, leaf length, leaf width, leaf count, and chlorophyll content were measured twice: 30 days post-transplanting and at final harvest. Leaf length and width were averaged from the largest leaf measurements, and chlorophyll content (SPAD value) was measured with a SPAD-502 Plus (Konica Minolta, Japan) by taking five readings from the largest fully expanded leaf and averaging the values. To compare the effects of biochar application on Lettuce growth and soil chemical properties, an analysis of variance (ANOVA) was conducted using SPSS Statistics. Post hoc comparisons between treatments were performed with Duncan's Multiple Range Test (DMRT) at a 5% significance level.

4. **Potato crop preparation and plant growing strategy.** The importance of this study is justified in African lands (where the lands are poorly or non-responsive soils), harsh climate and diseases (black rot). So, the potatoes much valued by farmers for food and income generation in Kenya. Potatoes are the second important staple food crop in Kenya, after maize, while kale commonly known as "sukuma wiki" in Swahili is considered one of the most important vegetables consumed and used to generate income for the farmers in the country. (*Kipkorir D.L. et al., 2022*)

4.1. Tests conducted in field conditions.

4.2 The climate is desert

4.3 Biochar type was from pyrolysis maize production and forestry.

4.4 Soil preparation. Kapchorwa on-farm demonstrating plats. The experimental crop field were applied for potato with the next substances: biochar; biochar + diammonium phosphate (DAP), and DAP. After that biochar was applied at the rate of 1 kg/m^2 or 10 tones/ha and then covered with soil using manual rakes. All the experiments were multiplied by three.

4.5 The potato seeding. The potato (variety Sherekea) planting was made with 250 mm, between row tubercule and 750 mm between rows. (*Kipkorir D.L. et al., 2022*)

4.6 Crop management. Weeding was done once for potatoes to eliminate uncontrolled plants. At flowering stage, they were sprayed with Dithane M45 every two weeks to prevent potatoes late blight, which is common during the wet season. When the crop was in flowering vegetable faze, were sprayed using Dithane M45 every fortnight for late blight prevention, which is common during wet season. The methodology to assess the agronomic crop parameters during the cultivation cycle was not described in the paper.

The results obtained will be presented in the next chapter in such a way to underline each crop yields and biochar influence on each plant part following the same structure made in this part.

RESULTS

1. ***The tomato crop results from experimental field*** *were divided in two seasons.*

In the first season of tomato crop*,* were no observable differences in the plant heights, except it tended to increase in the 27.6 t/ha. Root and shoot weights were significantly affected by the biochar rates. Compared to the control, it was observed that root weight was significantly decreased by 127.6% in the 13.8 t/ha whereas shoot weight decreased by 154.2% for the same treatment compared to control. Interestingly, the 27.6 t/ha biochar rate increased root weight and shoot weight by 26.0% and 7.6% respectively compared to the control. However, root and shoot weights observed in the 27.6 t/ha treatment were not significantly different from the control.

In the second season, there were no significant differences in the plant height and root weight among the treatments. However, shoot weight was significantly decreased by 77.0 % in the 6.9 t/ha compared to the control. Interestingly, the 13.8 t/ha significantly increased shoot weight by 19.9% whereas 27.6 t/ha has increased the same parameter by 10.2 % compared to the control. These increments in the 13.8 t/ha and 27.6 t/ha were not significantly different from the control. Averaged across the two seasons, there were no significant differences among controls, 3.5, 13.8 and 27.6 t/ha. However, 6.9 t/ha had significantly lower plant height (655.4 mm) than the 27.6 t/ha (870.2 mm). Overall, the biochar rate of 27.6 t/ha non-significantly increased plant height by 9.0% compared to control. On the other hand, root weight was non-significantly different among all treatments. With exception of 27.6 t/ha the biochar rates significantly had lower shoot weight than control (inorganic fertilizer). For instance, the 3.5 t/ha significantly decreased shoot weight by 86.4% whereas 6.9 t/ha and 13.8 t/ha decreased shoot weight by 308.2% and 80.5% respectively, compared to the control. (*Wacal C., et al., 2023*)

2.The growth of green bell pepper crops results from the experimental conditions.

Pepper agronomic variables in this case study, revealed improvements, particularly during the reproductive and maturity stages, with plants treated with 1% biochar (SB1) exhibiting enhanced growth and chlorophyll content, alongside increased flower and fruit yields. Notably, the 2% biochar treatment (SB2) yielded superior fruit weight and length results, suggesting the potential for biochar to enhance both the quality and quantity of green bell pepper fruits, thereby contributing to sustainable agricultural practices. (*Sanchez E. et al. 2024; Salma, U. et al., 2022*). Significant differences were found during reproductive stages (Stage 2) and maturity stage (Stage 3) in the number of leaves and their chlorophyll content (SPAD). At Stage 2 was noticed that plants corresponding to SB1 had a greater number of leaves than the control and the chlorophyll content was not influenced by the PSB ratio, compared to the control. On Stage 3, the plant biomass did not show significant differences between SB1 and SB2, but it did with SB0, but the chlorophyll content (SPAD) increased significantly with increasing PSB content (SB2), see Fig. 2. The presence of flowers and fruits is interconnected, but the differences where not significative between the reproductive and ripening stages, in the flowers number for the different treatments. In both stages, the green bell pepper plants treated with 1% biochar (SB1) showed a greater development of flowers compared to the other treatments. During Stage 2, the higher number of leaves and flowers per plant in samples treated with 1% biochar could be attributed to a specific physiological response to this lower biochar concentration (1% biochar promotes optimal soil environment for plant development during this crucial reproductive phase). This lower concentration could provide the necessary nutrients in a balanced manner that would promote the formation of a greater number of reproductive structures, such as leaves and flowers. (*Murtaza G. et al., 2021*). Biochar enhances plant growth by directly influencing root development through potential changes in soil quality. Additionally, it modifies the soil's ability to retain fertilizers. Other factors contributing to improving plant growth and yield with biochar include increased nitrogen use efficiency, greater cation exchange capacity, enhanced water retention, and increased mycorrhizal abundance (*Murtaza G. et al., 2021; Song D. et al., 2018*). On the other hand, in crops treated with 2% biochar and showing a lower number of leaves and flowers during the reproductive period, this higher concentration may generate some type of physiological stress in the plants. This stress could be related to nutrient saturation or an imbalance in the soil due to the high concentration of biochar, which may interfere with normal reproductive development processes. Previous studies have shown that excessive doses of biochar can adversely affect plant growth and development by altering the physical and chemical properties of the soil, as well as nutrient availability. (*Zhang M. et al., 2021*). The addition of high concentrations of biochar may negatively affect soil microbes by potentially inhibiting biological nitrogen fixation. These adverse effects could hinder seed germination, suppress crop growth and development, and ultimately compromise yield performance (*Murtaza G. et al., 2021*).

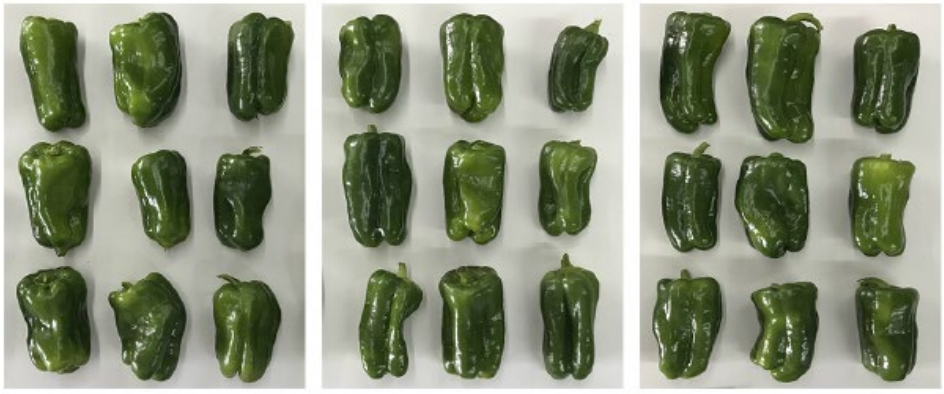

Fig. 2. The fruit development stage representation for each applied treatment. (*Sanchez E. et al., 2024*).

Considering the fruit weight, the SB2 treatment showed average higher values compared to the control and SB1 treatments. It was also observed that the fruits obtained from the SB2 treatment had a significantly greater length compared to the control (SB0) and SB1 treatments. They recommended a dose of 5 t/ha to balance soil improvements without negatively affecting pepper fruit production.

3.Lettuce crop results from experimental conditions, in two seasons.

The results were divided in two categories: lettuce growth and crop yield, also is analysed the effected of biochar co-applied with NPK fertilizers. Statistically significant differences in lettuce growth were observed among treatments during the second year's harvest. ***In the first crop season***, crop yield increased in all biochar-treated groups compared to the NPK treatment, but biochar addition increased leaf length and leaf width after harvesting. However, leaf number was not statistically different between NPK treatment and biochar co-applied with NPK treatments. The biochar co-applied with NPK treatments increased the fresh weight compared to the NPK treatment alone in the first crop season. This is due to the effect of biochar on soil properties such as pH and CEC, thereby influencing crop production and growth. (*Lehmann J. et al., 2003; Chan K.Y. et al. 2008; Major J. et al., 2012*) In that study has been proven that the lettuce growth increased as the exchangeable cation increased by biochar in the biochar co-applied with NPK treatments.

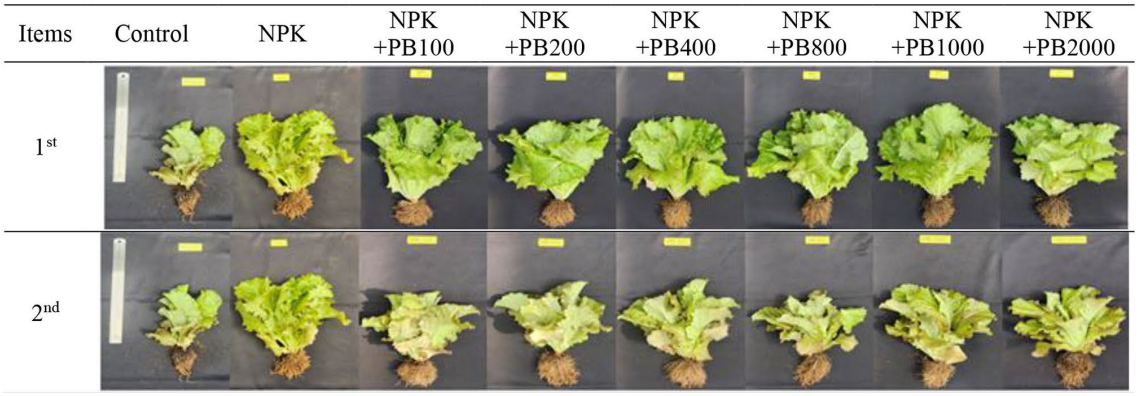

Fig. 3. Lettuce development stages during the experimental study (*Lee Y.N. et al., 2024*)

In the second crop season, fresh weight was higher in the biochar-treated groups compared to the NPK treatment. However, in the groups with biochar application amount of 800 kg or more, lettuce fresh weight decreased by 13.15% (PB800), 12.97% (PB1000), and 19.87% (PB2000), if are compare the second crop season compared to the first. A similar trend was observed in crop yield results. However, in the second crop season, when the biochar application amount was 800 kg or more, crop yield decreased compared to the first crop season. This is attributed to the increase in soil pH and EC caused by the excessive addition of biochar. Biochar has high alkalinity, and excessive addition to soil can affect soil pH. (*Biederman L.A., Harpole W.S., 2013*) Biochar and its effects on plant productivity and nutrient cycling: a meta-analysis. GCB bioenergy 5(2):202–214) An increase in soil pH can reduce the availability of micronutrients such as iron, manganese, and zinc, preventing plants from absorbing sufficient amounts of these essential elements (*Cao Y., et al., 2018; Lee Y.N. et al., 2024)*.

4.Potato crop productivity. Plot treated with biochar and DAP had higher potato yields (48%) compared to the other treatments (biochar 15.2% and DAP 22.9%). These results are influenced by biochar properties to retained nutrients over a long period of time, as well as ammonium form DAP fertilizers, increase cation exchange capacity (CEC) the soil pH was higher in the plat treated with biochar and phosphorus, water holding capacity.

CONCLUSIONS

Based on the above-presented results, important observations were drawn, which now have a scientific base:

- From the biochar crop administration and field data administration, are different and adequate to other experience: in some cassis the soil and biochar analyse was missing; the water quality and administration is missing; the plant parts analysis also is missing; the soil after crop harvesting is not presented. So, some of them cannot be reproduced to filling the gab, or to be used by others farms from that area.
- The influenced of the environmental factors, from the field crop research, is also missing and the nutrient balance and their migration cannot be established;
- The biochar testing IBI guidelines, are not mentioned, because the experiments were conducted before the publication of the guidelines.
- In most of the cases the biochar administration is made after applying fertilizers (solid fertilizers), so the biochar activation is naturally made, during the watering faze form rain. In some cases, was respect the fito-nutrient substance analyse flow, presented in Fig. 1. So, it is possible to establish the fito-nutrient balance and their influence in the crop yield, over all also the soil microorganism evolution and environmental impact on short/long therm.
- The biochar testing standard IBI, das not include all chemical compounds, needed to efficient administrate it in agriculture, some adjustments must be made so the soil quality to not be affected or the crop productivity.
- The crop experimental data management procedure must be adapted to collect, analyse and identify most important plant vegetative factors, using the AI systems, starting for basic experimental conducted that leading the way.

Writing this paper, give us the occasion, to understand the method that could be applied to structure and centralize the experimental data obtained on biochar application research conducted in different: conditions, biochar quality, technologies, administration, crop management and experimental data gendering methodologies, data interpretation and corelation. So far, this structural approach can be easily applied in more detailed view for each crop and can be adapted to its specification (lettuce crop data acquisition).

All the vegetable crop yield was increased, if it takes in the consideration the pour soil type and hard environmental conditions, fact that for those farmers represents a starting point. The biochar administration rates were well documented and applied in order to confirm some important theories (for hard environmental and experimental conditions).

Some relevant studies in this field, indicate that biochar used as amendments may have lack of nutrients, which does not improve growth parameters, especially in pepper crops. Jaaf et al. 2022, evaluated the effects of corn cobs and bird droppings biochar on red pepper growth and soil properties, and concluded that bird droppings, whether used alone or combined with biochar at the same doses, enhanced soil quality and stimulate pepper crop development. So, biochar application alone had a limited effect on plant growth, due to leak of necessary nutrients quantities in order to conduct the plant to optimal plant development, suggesting its combination with mineral fertilizers or nutrient-rich organic materials. In a similar study. Tito et al., also were investigated the effect of biochar produced from bird droppings on soil and pepper crops. They used different doses of biochar in the soil (0, 2.5, 5.0, 7.5, and 10 t ha−1) and observed improvements in soil chemical properties and pepper growth.

A holistic approach, nowadays is directed to each crop necessary, biochar source and composition, biochar administration strategy, crop management (especially: the foliar fertilizers, insecticide administration, rain water quality, earth fungi and bacteria evolution) and its impact on short/long therm.

In conclusion, the agro-industrial sub-products as a long-term organic amendment, that offers both economic and environmental benefits, when is applied with a fertilizer, also providing a sustainable alternative for its utilization, especially for poor countries (Africa, America, India, etc.). The strategy to improve cultivation productivity, especially for non-responsive soils, is much complex and, it must take in

to consideration the microfauna from the soil and crop rotation, in order to fully contribute to the sustainable management of agricultural resources.

Further, will be conducted dedicated fully vegetable studies to assess the biochar long-term effects of vegetable crops and its feasibility under different soil and crop conditions (field, greenhouse, etc.), using the same structure and trying to follow the nutritional flow substance, especially for potato crop (that needs special subtract growing conditions and irrigation). (*Kipkorir D.L. et al., 2022)*

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RESEARCH ON MONITORING PARAMETERS OF SOWING MECHANIZATION PROCESSES
/
CERCETĂRI PRIVIND MONITORIZAREA PARAMETRILOR PROCESELOR DE MECANIZARE A LUCRĂRILOR DE SEMĂNAT

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ABSTRACT
It is considered that sowing is the first link in the technological chain, with a significant share in limiting the level of plant production. Preparations for sowing begin immediately after harvesting the preceding plant, in terms of the land and immediately after harvesting, in terms of the seed, and the completion of these preparations takes place on the day of sowing. Determining and monitoring functional parameters involves: tracking phenomena in the context of correlated mutual influences, based on measuring a quantity in an experimental process; testing finished products and monitoring processes. Depending on the purpose and applications, the data acquisition and processing system (DAPS) may have in its structure one or more channels for collecting and processing data characteristic of a quantity or/and control links through feedback.

REZUMAT
Se apreciază că semănatul este prima verigă din lanţul tehnologic, cu pondere însemnată în limitarea nivelului producţiei vegetale. Pregătirile pentru semănat încep imediat după recoltarea plantei premergătoare, în ceea ce priveşte terenul şi imediat după recoltat, în ceea ce priveşte sămânţa, iar încheierea acestor pregătiri are loc în ziua semănatului. Determinarea şi monitorizarea parametrilor funcţionali presupune: urmărirea unor fenomene în contextul influenţelor reciproce corelate, pe baza măsurării unei mărimi într-un proces de experimentare; testarea produselor finite şi monitorizarea unor procese. În funcţie de scop şi aplicaţii, sistemul de achiziţie şi prelucrare a datelor (SAPD) poate avea în structura sa unul sau mai multe canale de culegere-prelucrare a datelor caracteristice unei mărimi sau/şi legături de control prin reacţie.

INTRODUCTION
Seed obtained from own production or purchased from specialized units, stored in appropriate conditions, conditioned and treated against diseases and pests, bacterized, etc. ensures the possibility of sowing on time.

Along with these two basic conditions, it is also necessary to prepare sowing machines, tractors and other equipment that contribute to the establishment of agricultural crops. Each crop has a certain optimal time in which the sowing work must be carried out. In our country, this time is dictated primarily by the thermal factor (there is a certain minimum germination temperature), but the humidity factor, which must be found in the soil at the seed level, should not be neglected either *(Marin et al., 2012; Cujbescu et al., 2016; Manea et al., 2019)*.

It is said that sowing is of quality when the land has been prepared in advance, has accumulated sufficient water reserves and has favoured nitrification activity, and the preparation of the seedbed has been carried out the day before or on the day of sowing with tools that do not turn the soil, but only ensure loosening to the level at which the seed is buried in the soil. Under these conditions, the seed is buried on a layer of settled soil, with the possibility of raising water to the seed level through capillary rise, placed in intimate contact with the soil, and above is the layer of loosened soil through which air and heat easily penetrate and which can be easily crossed by the young plant *(Marin et al., 2012; Cujbescu et al., 2016; Cujbescu et al., 2017)*.

During the sowing work, certain “anomalies” may occur, among which we can list:

- inconsistent distribution of the quantity of seeds or the number of seeds required per hectare, for each type of crop for which they are intended to work;
- uneven distribution of seeds;
- damage to seeds (breaking, crushing) during their distribution;
- the sown rows are not straight or the distance between them is not kept the same along their entire length;
- the seeds are not buried to the depth required by the agrotechnical technique for each crop or the established depth is not uniform over the entire sown area;
- the sown area has errors, i.e. it has unsown portions or portions sown twice (crossed rows);
- the organs that perform the burial of seeds become clogged with soil or plant debris.

The quality of the sowing work is constantly controlled during its execution, in order to permanently take measures to remedy any deficiencies, since after sowing, no further intervention is possible *(Cujbescu et al., 2015; Cujbescu et al., 2020)*.

MATERIALS AND METHOD

Monitoring of functional parameters requires a data acquisition system as well as a user interface *(Lv et al., 2018; Xie et al., 2021)*. Data acquisition and processing systems are systems of varying complexity, designed, developed and used for the purpose of: tracking phenomena in the context of correlated mutual influences, based on the measurement of a quantity in an experimental process; testing finished products and monitoring processes. The description of the general structure of a data acquisition and processing system is presented in Fig. 1.

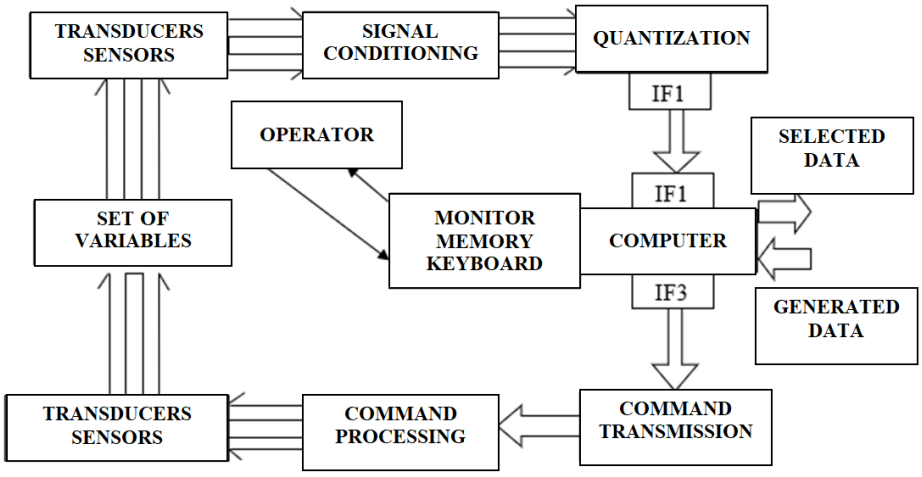


Fig. 1 - General structure of a data acquisition and processing system

Depending on the purpose and applications, the data acquisition and processing system (DAPS) may have in its structure one or more channels for collecting and processing data characteristic of a quantity and/or control links through feedback *(Lv et al., 2018; Bai et al., 2022)*.

In this context, the signal collection and processing channel includes:

- transducers and sensors, which transform the quantity to be studied into an electrical signal;
- signal processing system, in which the primary electrical signal is associated with a numerical code;
- signal quantization system, which performs signal sampling and analog-digital conversion;
- computer, which takes over the primary data through the standardized interface IF1

The computer manages the acquisition process, stores the data, displays primary and processed data, receiving commands from the operator. Through an appropriate interface IF2, the computer can communicate selected data to other computers of similar hierarchical rank, to powerful supervisory and management computers, or receive instructions from other computers .

The control channel is present in most DAPS systems, ensuring optimal, adaptive control of the process, the characteristic values of which have been collected. This channel includes:

- the computer that issues the prescribed values of the controlled quantities;
- the transmission of commands through signal channels and specific protocols;
- the system for processing commands, which also includes digital-analog conversion;
- the execution elements that perform the correction actions of the controlled quantities.

The transmission, storage and processing medium being electrical (the information is included in an electrical signal characteristic: amplitude, logic level, frequency, phase of voltages or electric currents, electromagnetic field) all quantities are introduced *into the acquisition* and processing system after a first transformation from a non-electrical quantity into an electrical quantity. Some electrical quantities are compatible, only needing to be collected and conditioned (e.g. voltage, electric current), and others (electrical power, circuit parameters) need to be converted into common information carriers (voltage, current).

A large part of the quantities are non-electrical, implying the use of *transducers* (sensors) that transform the respective quantity into an electrical representation, which contains unambiguously, within known precision limits, the value information on the original non-electrical quantity.

Transducers can perform:

- the function of transforming a non-electrical quantity into an electrical quantity;
- translation and conditioning of the obtained electrical signal (integrated transducers);
- translation, signal conditioning, analog-digital conversion and primary data processing (intelligent transducers).

From the point of view of the operating principle, transducers are:

- parametric, having as an electrical quantity output a circuit parameter (resistance, inductance, capacitance);
- generators, having as an electrical quantity output a voltage or electrical charge;
- radiation, based on the interaction between different forms of radiation (infrared, ultrasound, laser, microwave, nuclear) and the non-electric quantity to be measured;
- digital, which directly produce numerical codes.

Transducers are characterized statically (measurement limits, accuracy, sensitivity, linearity) and dynamically (transfer function, response time, frequency band). Usually, a non-electrical quantity can be transformed into an electrical quantity based on different principles, and the choice of the transducer is made based on the analysis of the price-performance ratio (*Xie et al., 2021)*.

A special problem is the noise protection of the primary signal capture and transmission path through appropriate grounding and shielding procedures.

A main disadvantage of on-board monitoring systems of functional parameters is the significant increase in the cost price of the agricultural machine.

RESULTS

Specific working parameters of sowing machines and technical methods of implementation

The sowing depth is specific to each crop, but it also depends on the soil texture, the degree of humidity and the level at which it is found in the soil, the type of germination (epigeic or hypogeic), the length of the coleoptile, the size of the seed (the amount of reserve substances in the grain), etc.

As a general rule, it is considered that the sowing depth should be equal to ten times the thickness of the seed because small seeds, with small reserves of nutrients, will give rise to germs with less penetration power than large ones. The sowing depth that must be respected when establishing the main agricultural crops is presented in table 1.

Table 1

Established Crop	Seeding Depth [m/s]	Established Crop	Seeding Depth [m/s]
Wheat	2,5 ÷ 5	Beet	1,5 ÷ 4
Rye	2 ÷ 3	Rapeseed	1 ÷ 2
Barley	3 ÷ 5	Barley	2 ÷ 3
Oats	3 ÷ 5	Sunflower	5 ÷ 8
Peas	3 ÷ 8	Soybean	3 ÷ 4
Corn	4 ÷ 8	Beans	5 ÷ 7
Alfalfa	1 ÷ 2	Flaxseed	2 ÷ 4

Very important is the *uniformity of the sowing depth*, which can be ensured by good levelling and crumbling of the soil and by identical, *correct adjustments for all sowing coulters*. Deviations of only ±1 cm from the established optimum depth are allowed. Also, great difficulties are encountered in achieving very shallow sowing depths, for which it is necessary to equip the seeders with coulters with a skid that limits the sowing depth.

The coulters of sowing machines have the role of introducing the seeds dosed by the distribution devices into the soil, *at the depth* required by the agrotechnical conditions, so as to create optimal conditions for germination and then for plant growth.

In the process of work, regardless of their type, the coulters must maintain a *constant working depth*, as well as complete coverage of the seeds with a layer of loose and moist soil.

The forces acting on a cultural coulter during work are (fig. 2 a): R_a – the resultant of the elementary resistances to compression and splitting of the soil; R_s and R_d – the resultants of the elementary resistances to compression and lateral displacement of the soil; F_a, F_1 and F_2 – the resultants of the friction forces acting on the leading edge and lateral flanks of the coulter.

In addition to the force R, the following forces also act on the coulter-support arm system (fig. 2 b): G_b – weight of the coulter-support arm system; P – traction force; T – force developed by the spring (in the case of coulters equipped with springs).

The working stability of the coulter is ensured if:

$$\vec{R}_t = \vec{R} + \vec{G}_b = \vec{P} \tag{1}$$

passes through point O. Respectively if:

$$G_b L_1 = R h \tag{2}$$

If $G_b L_1 > R h$ or if $G_b L_1 < R h$, the coulter tends to increase or decrease the working depth, respectively.

In real working conditions, the force R changes both its value and direction, changes caused by both the working depth and the soil inhomogeneity. Maintaining stability during work is achieved by ensuring a sufficient G_b value so that condition (2) is satisfied.

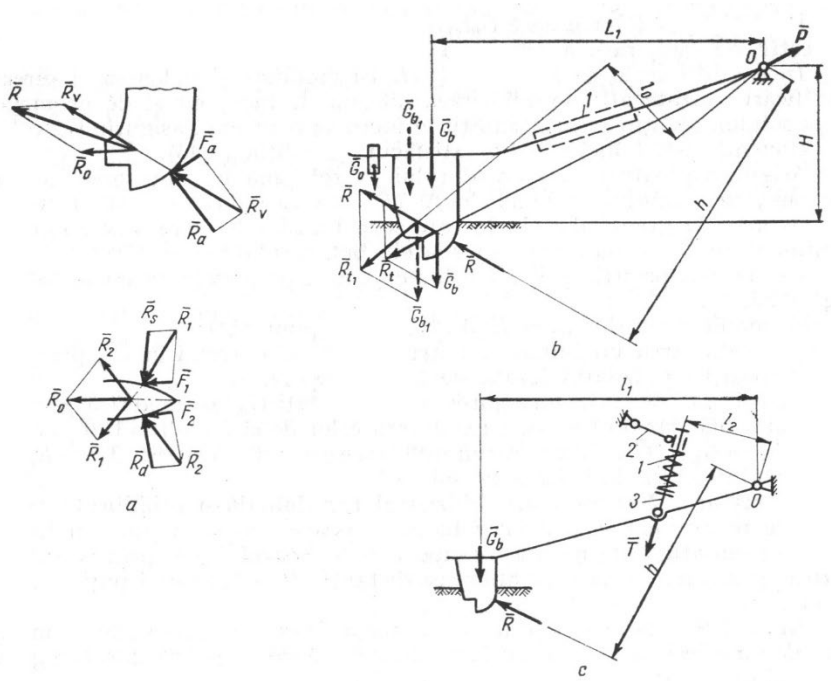


Fig. 2 – Forces acting on the coulter during work

Ensuring the penetration of the coulter into the soil to the required working depth under real operating conditions (r is variable), based on mechanical and experimental studies *(Cujbescu et al., 2016; Cujbescu et al., 2021)*, can be achieved by:

- increasing the weights G_b, for this purpose the coulters are provided with additional weights;
- increasing the pretension of the springs with which some coulters are provided (fig. 2 c);
- changing the distance H between the soil and point O;
- changing the angle of penetration of the coulter into the soil, by changing the position of the coulter relative to the support arm.

Seed spacing (seeding rate) - the amount of seed required per hectare is also called the seeding rate or the rate per hectare and depends on the plant species, sowing time, climatic conditions, soil fertility, seedbed preparation, twinning capacity of plants and sowing method *(Cujbescu et al., 2015; Cujbescu et al., 2016; Cujbescu et al., 2021)*.

The amount of seed required per hectare "*Q*" is calculated according to the relationship:

$$Q = \frac{D \cdot MMB \cdot 100}{P \cdot Cg} \quad (3)$$

where:

D - plant density per unit area; MMB - mass of 1000 grains; P - physical purity; C_g - germination capacity.

It is necessary for the seeder to distribute the seed uniformly, making tests and adjustments for each coulter, until each distributes a quantity $q_b = q/n$, where q is the quantity of seed distributed per 100 m^2 and n - the number of coulters. It is very important to achieve the values of distribution uniformity across the working width of the seeder (under current equipment conditions 92% for grasses, 95% for legumes and textiles and 96.5% for cereals).

Row spacing - the normal development of any crop plant requires that it has a certain vital space, that it does not compete for food, water and light with its peers or weeds. For this, it is necessary to ensure a certain distance between rows and between plants in a row when sowing. In the case of crops sown in close rows (straw cereals, flax, etc.), this would mean that the distance between rows should be 3-4 cm. Reducing the distance between rows, in this case, is limited by the need for excessive soil compaction and the total lack of plant debris on the thickness of the seedbed, as well as by the difficulties in making sowing machines with these distances and maintaining quality indicators during sowing *(Marin et al., 2012; Manea et al., 2019)*.

In the case of tillage crops, reducing the distance between rows is limited by maintaining the possibility of performing mechanized tillage. Different schemes of sowing in strips are practiced in which weed control within the strips is carried out by herbicides, and in the interval between them, by hoeing.

Long-term experiences have established the best densities for each plant species, for different cultivation conditions. They can vary between 4-6 plants/m^2 for corn and sunflower and up to 2,500 plants/m^2 for flax for fiber and are differentiated by soil fertility and the provision of water (irrigated or non-irrigated).

For this purpose, all the properties of the seed must be well known and, first of all, its useful value (useful seed - S_u), which is conditioned by purity (*P*) and germination capacity C_g:

$$Su = \frac{P \cdot C_g}{100} \quad (4)$$

Machine travel speed - the optimal working regime of the aggregates corresponds to the gear at which the traction power is maximum, and the specific fuel consumption is minimum *(Cujbescu et al., 2017)*. Some works cannot be performed in the gears corresponding to the optimal regime, because, in these gears, the tractor travel speed is higher than the maximum speed at which agricultural machines can travel (technological speed). In this case, the optimal working regime of the aggregates is limited by the technological speed of the aggregate. The sowing speed is limited by the decrease in the seed burial depth. The qualitative work indices obtained at a speed of 9 km/h do not differ from the indices obtained at 5 km/h. Increasing the speed above 9 km/h required constructive modifications to the coulters and distribution devices. When sowing tillage crops, the travel speed of machines equipped with pneumatic distributors is limited by the peripheral speed of the distributor disc.

✓ ..**Measurement methods and chains used in experimental research**

Measurement method is understood as the set of principles and means on which a measurement is based in order for the result obtained to represent the value of the measured quantity as accurately as possible and to satisfy the requirements of use *(Voicea et al., 2009)*.

The main criteria for classifying measurement methods are:

- ***The method of comparison with the unit of measurement,*** after which they divide into *direct methods and indirect methods:*

Direct measurement methods are characterized by the fact that the value of the measured quantity is expressed directly as a result of comparison with a standard belonging to the same class, without resorting to relationships based on quantities of another physical nature.

Indirect methods are applied to those quantities for which it is not possible, or is not feasible through advantageous practical procedures, direct comparison with a reference quantity belonging to the same class. As a result, starting from a dependency relationship, a consequence of physical laws between such a quantity and other directly measurable quantities, indirect measurement consists of a series of direct measurements, followed by calculation operations corresponding to this relationship.

- ***The form of expression of the quantity***, according to which we have: analogy measurements and numerical measurements:

- *Analog measurement*: the signal that circulates through the measurement chain and carries the information is functionally linked to the quantity to be measured by a continuous law. Through the reading operation at the receiver, based on the prior calibration, the analogy indication is transformed into a number that expresses the numerical value of the measured quantity.
- *Numerical measurement:* in this case, the measurement operation leads to obtaining a number that, after a certain code (such as the binary code) indicates the value of the measured quantity.

✓ ***Measurement technique***, according to which there can be measurements by deviation, measurements by comparison, measurements by counting:

- *Measurement by deviation*: the method is of the analogy type and consists, in principle, in the deviation of a system from an equilibrium position that it has in the absence of the quantity to be measured, to another equilibrium position that it obtains in the presence of the quantity to be measured. The quantity is highlighted by the difference between the two equilibrium positions.
- *Measurement by comparison* consists of generating a known quantity that is compared with the quantity to be measured, and which is adjusted to equal it. The method is also called the zero method because by equating the comparison quantity with the one to be measured, their sum is zero.

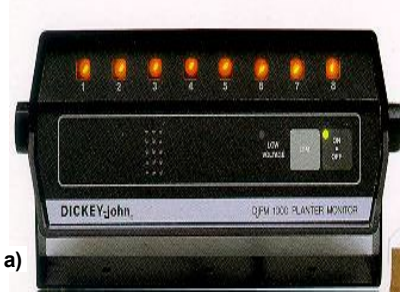
Measurement by counting consists of measuring the quantity of the quantity (counting its value).

✓ ***The reference origin of the measurement***, according to which there can be absolute measurements and differential measurements:

- *Absolute measurement* is that at which the measurement base is an absolute zero for which the measured quantity is not achieved.
- *Differential measurement* is that at which an arbitrary measurement base is chosen as the origin and the value of the respective quantity is established against it.
- *In experimental research*, all methods are used, with numerical measurement currently having a greater weight and, to some extent, analogy measurement.

✓ **On-board monitoring systems**

Externally, extensive research has been conducted in this field and the main agricultural machinery manufacturers such as: John Deere, Fiat, Valmet, Case, Deutz-Fahr, Lamborghini, New Holland, Renault, Ford, Sulky, Ribouleau – Monosem, Gaspardo, Roger, Nodet, Sicam, MaterMacc produce equipment equipped with on-board computers that provide monitoring and driving assistance *(Lv et al., 2018; Xie et al., 2021; Shenghe Bai et ak., 2022)*.



a)

b)

Fig. 3 – Optional monitors (Monosem seeder)
(https://www.monosem.com/ - Prospects)

Fig. 4 – Speed control device
(Prospects company Ribouleau)

The pneumatic precision seeder for sowing and fertilizing 8-row MONOSEM sows, produced by the Ribouleau company in France, is equipped with an electronic system for controlling the seed distribution and also allows the digital display of the speed, the worked area (partial and total), (figure 4).

The MaterMacc company in Italy presents a machine for sowing 8-row sows, equipped (optionally) with three electronic devices that allow the display of the total or partial worked area, the working speed and the distance travelled, (figure 5), the interruption of the distribution on one or more rows (figure 6), or simply counts, autonomously (self-powered), the number of hectares sown (figure 7).

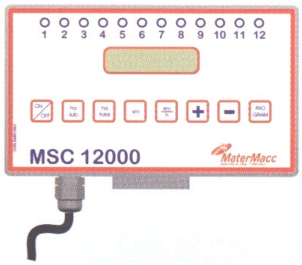


Fig. 5 - Monitor for viewing the area, speed and distance covered

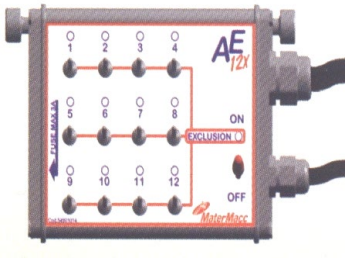


Fig. 6 - Device that interrupts the distribution on one or more rows
(https://www.matermacc.it/en_in/ - Prospects)

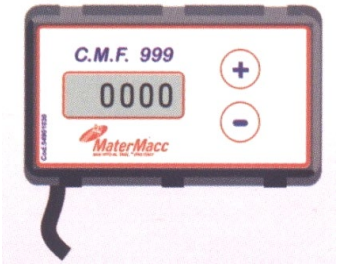


Fig. 7 - Electronic counter for the worked area

The Maxsem seeder manufactured by the Rau Sicam company in France is equipped with a minicomputer (figure 8) that can display the time, the number of kilometres travelled, the working speed, the number of hectares worked per hour, as well as the proper functioning of the sowing sections

Fig. 8 - Maxsem seeder monitor
(Prospects company Rau Sicam)

Fig. 9 - Free Flow seeder monitor
(Prospects company Roger)

The French company Roger equips its Free Flow seeders with equipment (figure 9) that can provide the following services: tramline management, control of the worked area, control of the rotation of the grooves and the exhauster.

Gaspardo seeders, produced in Italy, can be equipped either with a small electronic counter (figure 10 a or b), which displays the worked area, or with (optionally) a complex monitor (figure 11) which of course increases the cost price of the machine.

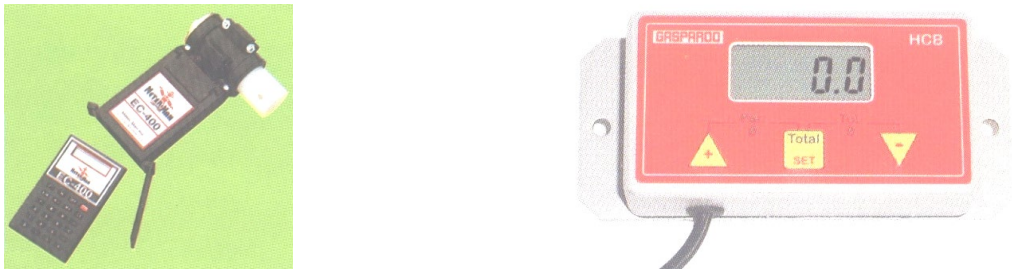


Fig. 10 - Types of electronic area meters (Gaspardo seeders)
(*https://www.maschiogaspardo.com/ - Prospects*)

The Sulky Tramlines seeder, manufactured by the Sulky company in Germany, allows the on-board display of the partial or total area worked and an alarm in the event of an anomaly in the distribution process or in the operation of the exhauster (fig. 12).

Fig. 11 - Optional monitor of the Gaspardo seed drill
(*https://www.maschiogaspardo.com/ - Prospects*)

Fig. 12 - On-board monitor of the Sulky Tramlines seed drill (*Prospects company Sulky*)

CONCLUSIONS

Sowing is a very important work in the overall agricultural work carried out within an agricultural campaign, since the quality of the sowing work influences to the greatest extent the production that is desired to be obtained.

As a result, monitoring the parameters of the work processes of sowing work has become a necessity and as previously presented, most major companies producing agricultural machinery have assimilated into production sowing machines and equipment equipped with transducers, acquisition systems and monitoring of functional parameters.

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ASPECTS REGARDING THE EVALUATION OF THE PLANT MATERIAL CHARACTERISTICS FOR THE PRODUCTION OF ENERGY PELLETS
/
ASPECTE PRIVIND EVALUAREA CARACTERISTICILOR MATERIALULUI VEGETAL ÎN VEDEREA OBȚINERII DE PELEȚI ENERGETICI

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ABSTRACT

The European Union and its member states are increasingly focusing on biomass and how it can support the transition to a sustainable and climate-neutral economy. The paper presents the importance of using renewable sources, as well as aspects regarding the evaluation of the characteristics of plant material in order to obtain energy pellets.

REZUMAT

Uniunea Europeană și statele sale membre pun din ce în ce mai mult accentul pe biomasă și pe modul în care aceasta poate sprijini tranziția către o economie sustenabilă și neutră climatic. Lucrarea prezintă importanta utilizării surselor regenerabile, precum si aspecte privind evaluarea caracteristicilor materialului vegetal în vederea obținerii de peleți energetici.

INTRODUCTION

Lately, human progress is increasingly intertwined with heightened environmental exploitation aimed at acquiring additional resources, especially in the field of energy generation *(Cifuentes, G. R. et al., 2024).*

Greenhouse gas (GHG) emissions represent a serious threat in terms of climate change, with potentially disastrous effects on humanity. The use of renewable energy sources (RES), together with improved energy efficiency (EE), can contribute to reducing energy consumption, reducing greenhouse gas emissions and, consequently, preventing dangerous climate change.

The European legislative framework in the field of energy and climate has created the context for the assumption of commitments by Member States that will lead to the achievement of community objectives.

By adopting the Paris Agreement in 2015 and assuming the resulting commitments by the signatory Member States, the fourth EU energy package – Clean Energy for All Europeans – entered into force in 2019, which laid the foundations for the European Green Deal in 2020. The European Union has set energy and climate objectives for 2030, as follows:

- The objective of reducing domestic greenhouse gas emissions by at least 40% by 2030, compared to 1990;
- The objective of a 32% share of energy consumption from renewable sources in 2030;
- The objective of improving energy efficiency by 32.5% in 2030;
- The objective of interconnecting the electricity market at a level of 15% by 2030.

The EU's fifth energy package, Ready for 55, published in 2021, updated Europe's climate ambitions, setting a target of reducing greenhouse gas emissions by 55% in 2030 compared to 1990 levels, with a view to achieving climate neutrality at European level by 2050, making Europe the first climate-neutral continent.

The EU's overall target for the share of RES in the energy mix by 2030 is 42.5% (with an indicative additional contribution of 2.5%), to reach the target of 45%. Romania's assumed objective for the share of RES in gross final energy consumption by 2030 is 38.3%.

Romania has committed to a net reduction of GHG emissions of 78% for 2030, and 99% by 2050 compared to 1990 levels.

At the national level, as medium and long-term programmatic targets, Romania's objective regarding the share of energy from RES in gross final energy consumption for 2035 is 44% and 73% for 2050. (*Romania's Energy Strategy 2025-2035, with a perspective of 2050*)

Biomass, considered as an energy resource, is fundamentally different from other non-fossil energy sources (e.g. wind energy). It generates energy and by-products similar to those of fossil resources. Biomass also has a very important use as a source of food and raw material for industry, uses that must be correctly correlated with the use for energy purposes, concomitantly with the observance of the principles of sustainability.

Biomass represents the vegetal component of nature. As a form of storing the Sun's energy in chemical form, biomass is one of the most popular and universal resources on Earth. It provides not only food, but also energy, construction materials, paper, fabrics, medicines and chemicals. Biomass has been used for energy purposes since man discovered fire. Today, biomass fuel can be used for various purposes – from heating rooms to producing electricity and fuels for cars and airplanes.

According to the definition given by DIRECTIVE (EU) 2018/2001 OF THE EUROPEAN PARLIAMENT AND OF THE COUNCIL of 11 December 2018 on the promotion of the use of energy from renewable sources, biomass is "the biodegradable fraction of products, waste and residues from biological origin from agriculture, including vegetal and animal substances, from forestry and related industries, including fisheries and aquaculture, as well as the biodegradable fraction of waste, including industrial and municipal waste of biological origin".

Under appropriate industrial processing conditions, freshly harvested biomass can be converted into products similar to natural gas or liquid or solid fuels. By applying various transformation processes, such as combustion, gasification or pyrolysis, biomass can be transformed into "bio-fuels" for transport, "bio-heat" or "bio-electricity".

In recent years, wood pellets became an important fuel to produce heat and energy around the world. These are considered as an option for competitive fuels since its higher fuel density translates into reduced transport and storage costs (*Pinho, R. et al., 2025*).

MATERIALS AND METHODS

Composition of cellulosic biomass types: cellulosic biomass is composed of cellulose, hemicellulose, lignin and a percentage of extractives, as shown in figure 1 for a series of representative examples of agricultural residues, wood, municipal waste and herbaceous plants (*Popa V. I. - Biomass as a Source of Energy and Chemical Products, "Gheorghe Asachi" Technical University of Iasi*).

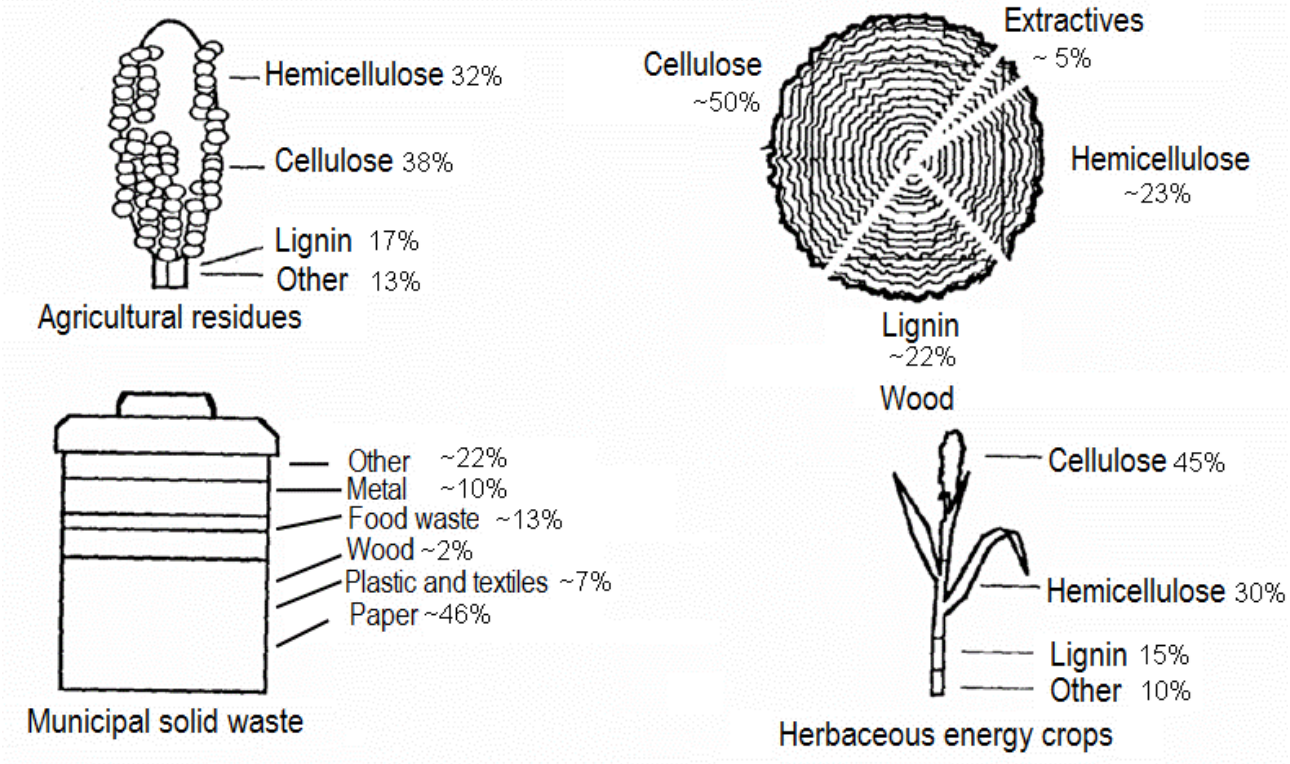

Fig. 1 – Composition of the most common types of biomass

(*Popa V. I. - Biomass as a Source of Energy and Chemical Products, "Gheorghe Asachi" Technical University of Iasi*)

The energy potential of biomass is assessed at a total of 318,000 TJ/year, equivalent to 7.6 million toe. This potential results from:

- agricultural waste (cereals, corn stalks, vine residues, etc.) - 63%;
- residues from forestry exploitation and firewood - 16%;

- residues from livestock farms - 8%;
- sawdust and other wood waste - 6%;
- urban household waste and residues - 7%.

Some of the important characteristics of different types of biomass are presented below, in Table 1.

Table 1

Biomass production indices from energy crops: an overview

(Manual – Renewable Energy Sources (2012))

Energy crop	Biomass type	Biomass production [t_{dm}/ha]	Humidity at harvest [%]	Lower calorific value [MJ/kg_{dm}]
Annual grass crops				
Corn	Corn residues	8.34-10.60	59-64	17
	Corn silage	19	34.5	17
Hemp	Stalks, leaves	5-15	50-60	18-25.6
Clover and other grassy forage crops	Stalks	8 1-6; 3.5	80 84.5-83.50	10.2 2.4
Perennial grass crops				
Arundo Donax (giant reed)	Stalks, leaves	20-30 15-35 20-35, 28 8,68	- 55-70 40 -	16-17.1 16-17 17.5 -
Miscanthus spp.	Stalks, leaves	11-34 15-25 15-30, 23	- 50-60 15-30, 25	17.6 17.3-17.6 17.0
Panicum Virgatum	Stalks, leaves	14-25, 19 10-25 10-25, 18	- 50-60 34-40, 35	- 17.4 15.9
Cynara Cardunculus (Artichoke)	Stalks, leaves	17-30 10-15, 12 7.12-14	- (20-30) 20 -	- 15.6 14-18
Lignocellulosic tree crops				
Poplar	Wood	9-12.5 9-13	50-60 50	17.7-18 18.6-19.1
Salix spp. (willow)	Wood	10-15 10-15, 12.5	50-60 50	17.8-18.4 18.4-19.2
Coniferous forests	Wood	35-60	40-50	18.8-19.8
Deciduous forests	Wood	36-60	40-50	18.5-19.2

Except in cases where direct combustion is suitable, raw biomass requires transformation into solid, liquid or gaseous fuels that can be used for the production of heat, electricity and as fuel for motor vehicles. This conversion is achieved through a series of processes that can be classified into four groups:

- physical (grinding, separation, drying, pelletization, briquetting, etc.);
- biological / biochemical (fermentation: anaerobic, aerobic, alcoholic);
- thermal (combustion, pyrolysis, gasification, hydrogenation);
- chemical (e.g.: production of biodiesel from vegetal or animal oils and fats).

To increase the density of solid biomass fuels and to allow automation of the combustion process, the transformation of biomass into pellets or briquettes is currently used.

Biomass densification consists of two stages:

– Compaction under pressure of the material to reduce the volume and agglomerate the material;

– The lignin contained within the wood material is activated by this pressure and “glues” the material without the need for an additional bonding agent.

Agglomeration is a technological operation widely used in the food, pharmaceutical, chemical, metallurgical industries, etc., which aims to increase the size of particle formations in a controlled manner, to ensure an internal structure and certain mechanical characteristics of the outer surface, density, compactness, porosity, etc. Depending on the way the agglomeration process is carried out, the characteristics and appearance of the final product obtained, the operation has several specific names: agglomeration, briquetting, granulation, pelletization, nodulation, synthesis, etc.

All compaction methods have as a common element the pressing operation, which produces the compaction of the particles of the primary material, resulting in an increase in the density of the final product (tablets, pellets, briquettes, etc.). Granulation by compaction is used when the aim is to obtain granules with high mechanical resistance and very precise geometric shapes and dimensions. The granules are formed under the action of pressure, created by forces applied from the outside, on the material in more or less closed molds. The shape and size of the holes or recesses of the mold defines the shape of the future granule.

Table 2

Characterization of agglomeration operations *(Rus, F. et al., 2008)*

Operation name	Characteristics
Compaction	High-pressure agglomeration method using pairs of rollers with smooth or profiled surfaces, which rotate towards each other in the feed area. The material is passed through the space between the rollers and, after pressing, increases its density.
Briquetting	Agglomeration method under pressure of up to 300 MPa, with or without binders, of powdery or granular materials, into briquettes with characteristic geometric shapes, at pressures depending on the characteristics of the raw material and those imposed on the finished product.
Tabletization	Agglomeration operation at high pressure 50-200 MPa, in individual dies, placed on a rotating disk, from non-wetted powdery materials, obtaining tablets.
Pelleting	Agglomeration operation at medium pressure, in ring or flat dies, periodically the material being forced to pass through the die holes, at the exit the noodles being cut. Cylindrical pellets of a determined length are obtained.
Extrusion	Agglomeration method at low and medium pressure, in which the material mixed with liquid binders is brought to a plastic state by kneading, after which it is forced to pass through the holes of a mold. The fact that the material is forced to flow throughout its mass results in a homogeneous structure of the extrudate, which has the shape of cylindrical noodles.

The pellet production process involves subjecting biomass to high pressures and forcing it through cylindrical holes in a die. When exposed to the right conditions, the biomass “fuses” into a solid mass. This process is called extrusion. Some types of biomass (mainly wood) naturally form good quality pellets, while other types of biomass (forage, herbaceous biomass, etc.) may require additives to serve as “binders” that hold the pellets together. However, the actual creation of pellets is a small step in the pellet production process. These steps include biomass crushing, moisture control, extrusion, cooling, and packaging/storage.

Pellets (fig. 2) are made by crushing sawdust, chips, branches, tree bark, or other biomass raw materials and pressing the resulting mixture through a die. The heat resulting from friction softens the lignin, which, when cooled, binds the mixture obtained from biomass. Since no binder is used for the manufacture of pellets, the lignin content of the biomass used is very important. Thus, from the composition of the pellets must not be missing resinous waste. According to the shape, the pellets can be with a circular or square section, the most widespread being the pellets with a circular section. Large-sized pellets require biomass with a high lignin content. For this reason, the most widespread are pellets with a diameter of 5 mm and a length of 5 mm or 10 mm.

Fig. 2 – Examples of biomass pellets

Briquettes (fig. 3) are usually rectangular or cylindrical in shape and are obtained by pressing together sawdust, chips, shavings or tree bark in a piston or screw press. The energy content of briquettes is about 17 GJ/tonne with a moisture content of 10% and a density of about 600-700kg/m^3.

Fig. 3 – Examples of biomass briquettes
(http://www.charcoalbriquettepress.com/blog/Calorific-Values-of-Biomass-Materials-for-Briquetting.html)
(http://www.woodbriquetteplant.com/news/Biomass-Briquette-Machine.html)

Table 3

The main characteristics of fuel pellets and briquettesl *(Kuokkanen, M. et al, 2009)*

Characteristics	Pellets	Briquettes
Raw material	agricultural waste; dry wood chips	agricultural waste; dry wood chips (raw material may be rougher due to larger product dimensions)
Shape	cylindrical	cylindrical or parallelepiped
Dimensions	diameter 6-12 mm, with a length 4-5 times larger	diameter 80-90 mm (cylinder) or 150x70x60 mm (parallelepiped)
Structure	stable, hard, dust-free	relatively crumbly, fragile
External appearance	smooth	rough, rough
Combustion heat, MJ/kg	16.8-18.5	16.9-17.6
Density, kg/m^3	600-700	600-700
Transportation method	in bulk, in bags	units
Handling	manual, automated	manual

The main advantages of densifying woody biomass are:

- Increasing the density of the compressed material (from 80-150 kg/m3 for straw or 200 kg/m3 for sawdust to 600-700 kg/m3 for final products);
- Higher calorific value and a homogeneous structure of the compressed products;
- Low moisture content (less than 10%).

The raw material used for the production of pellets and briquettes must meet certain physical characteristics, important in the densification process:

- Material fluidity and adhesive capacities (different additives, such as lubricants or binders, can be used to provide these characteristics);
- Predetermined particle sizes of the raw material (too fine a grinding can lead to increased cohesive properties, causing reduced material flow);
- Material hardness (too high particle hardness creates difficulties in the densification process);
- Adhesion (to strengthen the product structure).

Biomass properties

In order to use energy plants, modern industry has developed taking into account the way of handling and processing plants through various means, such as mechanical, thermal, electrical, optical and even sonic technologies. Despite the development of these machines, very little is known about the basic physical and mechanical characteristics of materials.

Knowledge of these properties must constitute important data, essential in: the creation of machines, structures and processes; analysis and determination of the efficiency of machines or operations; development of new products; evaluation of the quality of the final product.

Among the *physical properties of biomass*, the most important are:

- Density, which determines the behavior of materials, especially during their handling, which is why it is necessary to modify this property through specific processes;

- Apparent density, which can change depending on the material analyzed and its state of agitation;

- Bulk density, which directly influences the raw material to be processed. Due to the non-uniform shapes and dimensions of the raw biomass, the costs of transportation, storage and feeding into the processing flow facilities increase;

- Porosity, defined as the property of a granular material to have voids between its solid components;

- Compactness, which represents the degree of filling with solid material of the unit volume of porous material;

- Humidity, which can worsen the quality of biomass during storage, favoring the appearance of sprouting, scorching, mold, etc.;

- Hygroscopicity, which gives biomass the ability to adsorb and retain water;

- The calorific value of woody and agricultural biomass varies between 11000kJ/kg and 17000 kJ/kg. The calorific value of solid biomass fuels is much lower than that of conventional fuels (the average calorific value of diesel is 42.34 MJ/kg, and that of liquefied petroleum gas is 45 MJ/kg).

- The natural slope angle, which is an indicator of the flow of the material, being a function of the shape of the particles, friction forces and cohesion.

Among the *mechanical properties of biomass*, the most important are:

- Mechanical resistance, defined as the capacity of biomass to resist internal stresses arising in its structure as a result of external loads to which it is subjected;

- Bending stress, having a maximum value at a maximum distance from the neutral axis, representing the outer surface of the stem;

- Young's modulus, which characterizes the rigidity of biomass and whose value depends on: technical factors (type of stress, state of tension, magnitude of stress and direction of force), natural factors (porosity, chemical composition of the material, structure, texture);

- Poisson's ratio, which decreases proportionally to the magnitude of the load and is influenced by the same factors as the modulus of elasticity, generally having values between 0-0.5;

- Specific energy for shredding, which depends on the physical-mechanical properties, the type of stress in the shredding process and the degree of shredding;

The *chemical properties of biomass* are influenced by its composition. Biomass is made up of 88-99.9% organic compounds. The main chemical composition of biomass is: lignin ($C_{40}H_{44}O_6$) = 15-30%; cellulose ($C_6H_{10}O_5$) = 40-45%; hemi-cellulose = 20-35%. The limits of variation of the three main components are determined by the species. (*European Pellet Council, 2011*)

- Ash content is a very important quality characteristic for biomass, because this ash causes many operational problems during biomass processing and combustion. Plant ash (wood, firewood) has a high content of potassium, calcium, magnesium and other essential minerals, and can be used as a fertilizer. (*Jezerska L., et al., 2014*)

- The content of volatile substances is very important for assessing the thermal stability of the constituent elements of the organic mass of biomass.

- The fixed carbon content in agricultural biomass is generally between 15-25% and in woody biomass between 14-23%; (*Jezerska, L. et al., 2014*)

- The C/N ratio characterizes the capacity of organic waste to biodegrade;

- The C/H ratio is essential in choosing the optimal process for converting biomass into energy and for determining the CO_2 emission factor per unit of primary or useful energy (for woody biomass C/H = 7.5-8.5); (*European Pellet Council, 2011*)

- The content of heavy metals is very important in the energy recovery of biomass fuels, due to the negative impact of these harmful metals on the environment. (*European Pellet Council, 2011*).

Types of biomass mixtures for pelletization

Due to the high demand for pellets, as well as the availability and diversity of biomass from waste left over from the processing of agricultural and forestry products, new pellets made from various types of biomass mixtures have appeared on the market.

The use of forest and agricultural biomass for the production of agripellets is a new research direction. Worldwide, according to the latest research in the field, concerns are highlighted in the field of using biomass for energy purposes.

For the manufacture of pellets, biomass mixtures are used, such as: wood mixed with corn, meal, paper or cardboard, hay, with many types of straw (excluding rice straw), with sunflower plant residues, corn, branches of any kind, willow, miscanthus, residues from cleaning vines (vine ropes) or ornamental shrubs,

walnut shells, hazelnuts, chopped almonds, cherry pits, peaches, apricots, grape seeds, sunflower. Leaves, grass, as well as all other plant residues from cleaning forests, as well as many other plant residues, can also be pelletized.

Adding binders to biomass recipes for pelletization

In the pellet production process, various by-product materials can be used as binding agents to improve their quality. The quality of pellets (fig. 4) is determined by several key parameters such as moisture content, calorific value, fines content, mechanical durability, density, ash content and ash melting point. The values of these parameters are specified in standards. These define fuel classes, testing and sampling conditions, methods and quality assurance systems for the supply and distribution chains.

Fig. 4 Pellets quality: good (left); average (center); poor (right) *(Kofman, P.D. 2010)*

The physical and thermal parameters of pellets are influenced by the use of various binding agents or additives added during the manufacturing process. According to EU standards, additives that improve fuel quality, lead to lower gas emissions or stimulate combustion efficiency can be added up to a maximum of 2% of the total mass of wood pellets (*Samuelsson, R. et. al., 2012*).

Combining several components in the composition of pellets affects their physicochemical processes of combustion. (*Nyashina, G.S. et. al., 2025*)

In the pellet manufacturing process, additives act as a lubricant, increase production and decrease energy consumption per unit of product. Starch additives reduce the final moisture content of pellets to a much greater extent than lignosulphate additives. However, too much starch will make the final product extremely dry, which affects the mechanical strength of wood pellets.

Lignosulfonate additives result in the best mechanical durability values for wood pellets, but do not increase pellet density. Additives such as motor oil, corn starch, sodium carbonate, urea, vegetal oil and dolomite have the effect of decreasing the density of wood pellets. Corn starch and dolomite additives are the most effective in reducing the density of wood pellets. All types of starch (native wheat starch, oxidized corn starch, native potato starch, oxidized potato starch) increased the mechanical durability of wood pellets, with the best results being obtained with the addition of oxidized corn starch.

Lignosulfonate does not affect the calorific value of the pellets, but it significantly increases the sodium and sulfur content, and consequently increases SO_x emissions. Additives such as motor oil and vegetal oil have been shown to increase the minimum calorific value, while additives such as corn starch and dolomite have decreased the calorific value of the pellets. Wheat starch additives significantly reduce ash formation, in contrast to dolomite additives which increase the ash content and the ash melting point when burning wood pellets. Both corn starch and dolomite significantly increase carbon monoxide emissions.

When used in a mixture with different types of biomass, each additive results in unique physical and thermal characteristics. In this way, we can say that further rigorous research is needed to identify different mixtures of additives and biomass feedstocks that produce pellets with the desired physical and thermal characteristics, so that pellets remain competitive as a renewable energy option.

RESULTS

Mediavilla, I. et al. (2012) conducted a comparative study to analyze the influence of different additives (lignosulfonate, corn starch, and their different combinations) on the particle density and mechanical durability of pellets under similar initial conditions (same raw materials, same additive dosage, same moisture content, and same compression speed). The particle density varied between 960 kg/m^3 and 1130 kg/m^3, and the mechanical durability varied between 93.2% and 98.8% for different additives and their

combinations. The addition of lignosulfonate led to a higher mechanical resistance of the pellets, compared to the addition of corn starch. The results obtained in the tests on the particle density and mechanical strength of poplar wood pellets, with a specific pelletizing surface area of 5.6 cm^2/kW, using different additives, are summarized in Table 4 (*Mediavilla, I. et al., 2012*).

Table 4

Particle density and mechanical strength of poplar wood pellets using different additives (LS - lignosulfonates, MS - corn starch) *(Mediavilla, I. et al.,2012)*

Additives	Moisture [%]	Density [kg/m³]	Durability [%]
LS 2.5%	9.9	960	98.0
MS 2.5%	9.9	970	95.9
LS 5%	8.5	1080	98.8
MS 5%	9.8	960	97.3
LS 7%	9.5	1060	98.4
MS 7%	9.0	1000	96.4
MS 0.95% + LS 1.05%	6.3	1070	93.2
MS 1.94% + LS 1.06%	8.4	1030	95.6
MS 2.94% + LS 1.06%	8.0	1100	97.1
MS 3.93% + LS 1.07%	7.2	1130	97.1

Stahl, M. et al. (2012) found that the starch additive significantly increased the length of wood pellets when a cutting blade was not used. The use of raw materials with a larger particle size and a high moisture content reduced the density of the product, while high process temperatures and pressures increased its bulk density (*Stahl, M. et al., 2012*).

Tabil, L. et al. (2011) and Samuelsseon, R. et al. (2012) also found a negative inverse relationship between moisture content and bulk density. The bulk density of softwood pellets increased by 20-25 kg/m^3 with a 5% addition of bark additives. This is because bark contains 8-10 times higher concentrations of metals such as aluminum, iron and sodium than the wood stem. Other additives, such as lignosulfonate or various types of starch, decrease the moisture content of the pellets, thus contributing to the increase in the bulk density of the product (*Samuelsseon, R. et al., 2012; Tabil, L. et al., 2011*).

Jezerska, L. et al. (2014) in their research on the influence of starch on spruce sawdust pellets found that the hardness of the pellets increased with the amount of added starch. Pellets manufactured with a starch content of more than 10% reached hardness values that exceeded the range of the testing instrument, with a maximum capacity of 50 kg. The moisture resistance of the pellets increased with the added starch. Pure wood pellets had the lowest moisture resistance, absorbing 37.9% of the water during the test. The samples with an additive content of 20% were the least absorbent; the amount of water absorbed was 9.4%. It was also found that the density of the pellets decreased with the amount of starch added (*Jezerska, L. et al., 2014*).

Table 5

Mechanical properties and pellet density *(Jezerska, L. et al., 2014)*

Pellet composition	Durability index [%]	Hardness [kg]	Moisture [%]	Density [kg/m³]
100 % sawdust	70,3	40	37,9	1290
95 % spruce sawdust +5 % starch	80,9	50	20,3	1260
90 % spruce sawdust +10 % starch	84,4	> 50	14,7	1250
85 % spruce sawdust +15 % starch	94,0	> 50	14,7	1590
80 % spruce sawdust +20 % starch	99,2	> 50	9,4	1230

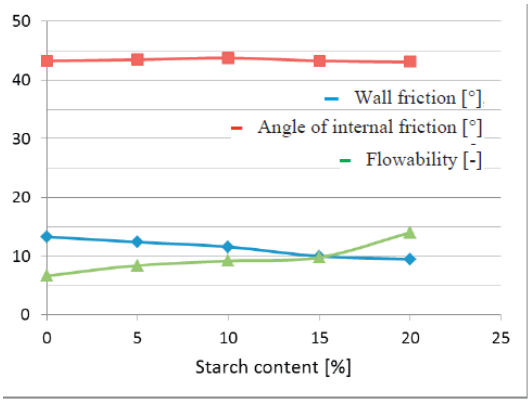

Fig. 5 The effect of adding starch on the properties of the mixture *(Jezerska, L. et al., 2014)*

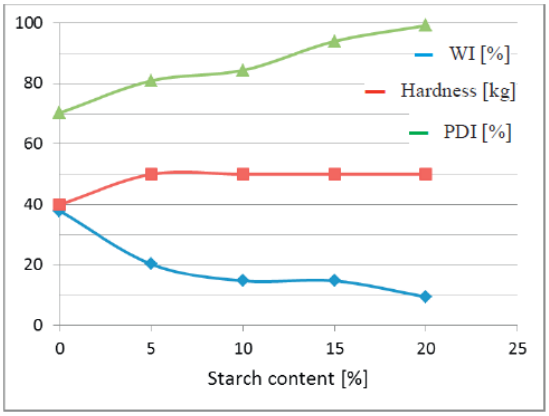

Fig. 6 The effect of adding starch on pellets properties *(Jezerska, L. et al., 2014)*

The range of density variation was between 1,230 - 1,290 kg/m^3. The average density value was 1,270 kg/m^3. The results obtained in their study are briefly presented in table 5 and figures 5 and 6. *(Jezerska, L. et al., 2014).*

CONCLUSIONS

The way we get our energy plays an important role in efforts to reduce pollution and climate change. On the other hand, renewable energy sources emit no greenhouse gases or only small amounts during their lifetime.

Biomass is the collection of non-fossil organic materials, which includes: wood, chaff, oils and vegetal waste from the forestry, agricultural and industrial sectors, but also cereals and fruits, from which ethanol can be made. Like the energies obtained from fossil fuels, the energy produced from biomass comes from the solar energy stored in plants, through the process of photosynthesis.

Except in cases where direct combustion is suitable, raw biomass requires transformation into solid, liquid or gaseous fuels that can be used to produce heat, electricity and as fuel for vehicles.

To increase the density of solid biomass fuels and to allow the automation of the combustion process, biomass is currently being transformed into pellets or briquettes.

For the manufacture of pellets, biomass mixtures are used, such as: wood mixed with corn, meal, paper or cardboard, hay, with many types of straw (excluding rice), with sunflower plant residues, corn, branches of any kind, willow, miscanthus, residues from cleaning vines (vine ropes) or ornamental shrubs, walnut shells, hazelnuts, chopped almonds, cherry pits, peaches, apricots, grape seeds, sunflower. Leaves, grass, as well as all other plant residues from forest cleaning, as well as many other plant residues, can also be pelletized.

The use of mixtures with various additives leads to changes in the physical characteristics of the pellets, namely, moisture content, density, mechanical durability, bulk density and pellet size.

When used in mixtures with different types of biomass, each additive results in unique physical and thermal characteristics. In this way, we can say that further rigorous research is needed to identify different mixtures of additives and biomass feedstocks that produce pellets with the desired physical and thermal characteristics, so that pellets remain competitive as a renewable energy option.

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ASPECTS REGARDING MINIMAL PROCESSING OF FOOD PRODUCTS USING VACUUM IMPREGNATION
/
ASPECTE PRIVIND PROCESAREA MINIMALĂ A PRODUSELOR ALIMENTARE UTILIZÂND IMPREGNAREA ÎN VID

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Keywords: *minimal processing, fresh-cut products, food products, vacuum impregnation*

ABSTRACT
Freshly harvested products are metabolically active and highly perishable. They suffer quality losses due to ripening and senescence processes, which are often associated with the development of spoilage microorganisms and other undesirable phenomena, which must be controlled to preserve quality and increase the shelf life of the product. Traditional methods of preserving fresh products negatively affect the sensory and nutritional characteristics. In this context, minimal processing has emerged as a response to the needs of consumers who increasingly demand food products of plant origin that retain their natural flavor, color, texture and contain fewer preservative additives. The paper presents aspects of minimal processing of food products using vacuum impregnation.

REZUMAT
Produsele proaspăt recoltate sunt active metabolic și foarte perisabile. Acestea suferă pierderi de calitate din cauza proceselor de coacere și senescență, care sunt adesea asociate cu dezvoltarea microorganismelor de alterare și a altor fenomene nedorite, care trebuie controlate pentru a păstra calitatea și a crește durata de valabilitate a produsului. Metodele tradiționale de conservare a produselor proaspete afecteaza negativ caracteristicile senzoriale și nutritive. În acest context, procesarea minimala a apărut ca un răspuns la nevoile consumatorilor care cer din ce în ce mai mult produse alimentare de origine vegetală care îşi păstrează aroma naturală, culoarea, textura şi conţin mai puţini aditivi de conservare. Lucrarea prezintă aspecte privind procesarea minimală a produselor alimentare utilizând impregnarea în vid.

INTRODUCTION

Fresh fruits and vegetables are important sources of essential vitamins, minerals and antioxidants. In recent decades, consumers have become more inclined to consume these products, as they are aware of their beneficial effects on human health and nutrition (*Gherghi, 1994; Hoffmann et al., 2014; Mahajan et al., 2014; Palumbo et al., 2022; Cirillo et al., 2023*).

Freshly harvested products are metabolically active and highly perishable. They suffer quality losses due to ripening and senescence processes, which are often associated with the development of spoilage microorganisms and other undesirable phenomena, which must be controlled to preserve quality and increase the shelf life of the product (*Barth et al., 2009; de Corato, 2020*).

The high water activity and the presence of nutritional factors associated with these matrices can also favor the development of pathogens (*Berger et al., 2010; Srisamran et al., 2022*). Due to its highly perishable nature, this category of products represents the food group with the second highest value of losses and waste across all stages of the supply chain (approximately 22%), surpassed only by root crops, tubers and oilseeds (*SOFA, 2019*). Therefore, post-harvest treatments are essential to minimize microbial spoilage and reduce the risk of pathogen contamination for fresh fruits and vegetables. Preservation technologies aim to reduce the intensity of metabolic processes such as respiration and transpiration, as well as the activity of pathogenic microorganisms, which are the main cause of decomposition processes. Fruits and vegetables with better sensory and nutritional attributes have a higher economic value. Consequently, inadequate preservation practices, in addition to causing significant losses of nutritional and qualitative characteristics, can have a negative economic impact along the entire supply chain, from growers to consumers (sorting, packaging, storage, transport, sale) (*Palumbo et al., 2022*).

Traditional methods of preserving fresh produce negatively affect sensory and nutritional characteristics (*Vinod et al., 2024*). The increasing consumer preferences for quality food have led to the significant development of various technologies in the food industry (*Ashitha and Prince, 2018*).

Given the increasingly demanding activities at work and the lack of time needed to prepare food after a day of work, consumers show an increasing preference for ready-to-use and ready-to-eat plant-based products, having a quality very close to that of freshly harvested products and containing only natural ingredients.

In this context, minimal processing has emerged as a response to the needs of consumers who increasingly demand food products of plant origin that retain their natural flavor, color, texture and contain fewer preservative additives. Minimal processing is defined as a trend of replacing classic thermal treatment processes with new, athermal ones, which involve the use of “gentler” techniques. To define minimal processing, in the specialized literature, the notion of "invisible" processing is also used, in order to emphasize the specificity of these techniques, following the application of which products are obtained that retain to a high extent the sensory and nutritional qualities of fresh food products (fresh-like). The concept of minimal fruit processing is associated with maintaining freshness by preserving the initial biological structure of plant tissues.

The expansion of minimal processing concepts has led to the production of new, renewed and improved products. This has stimulated the technological development of processes formulated and designed to obtain a greater diversity of minimally processed products. In this context, the fresh-cut food market has experienced significant growth, especially in developed countries, due to consumer demands for healthy and nutritious food products with a fresh appearance (*Ma et al., 2017; Yilmaz and Bilek, 2018*).

The quality of fresh-cut fruits and vegetables is strongly affected by physiological changes such as enzymatic browning caused by tissue damage and high respiration rates, and by physical factors including mechanical damage and removal of the outer protection, which favors faster weight loss, shrinkage, loss of color and appearance, and shortening of shelf life (*Siddiqui et al., 2011; Palumbo et al., 2022*).

Therefore, new innovative food processing technologies, such as immersion and vacuum impregnation techniques, are being investigated and implemented to sanitize, reduce enzymatic browning, improve texture, and utilize nutrients (vitamins, probiotics, minerals, organic acids, phenols, etc.) in the fortification of freshly cut fruits and vegetables, to preserve and improve the quality and extend the shelf life of these products (*Radziejewska-Kubzdela et al., 2014; Ashitha and Prince, 2018; Escobedo-Avellaneda et al., 2018; Chinnaswamy et al., 2020; Joshi et al., 2020*).

MATERIALS AND METHODS

Immersion treatments consist of immersing the product, with or without mechanical agitation, followed by removal of excess solution. This method is commonly used for whole, peeled, shredded and sliced products, as well as for more perishable products, as it favors the dispersion of the solution, covering the entire surface of the product, without causing additional damage (*Martín-Diana et al., 2007*). The removal of cell exudates, which can have a negative effect on the post-harvest quality of the products, is one of the major advantages of these immersion treatments. Depending on the food product subjected to minimal processing, the immersion process parameters that need to be optimized are immersion time, frequency, solute composition, temperature and solution concentration. A series of studies have tested immersion treatments with calcium (Ca) salts with the aim of extending the shelf life of the products. Ca enrichment brings with it a multitude of advantages, including reducing microbial growth due to decreased water activity, improving texture and acceptability, as well as preventing browning caused by oxidation phenomena and the development of undesirable aromas in freshly cut foods (*Soliva-Fortuny and Martín-Belloso, 2003; Alzamora et al., 2005; Mu et al., 2022; Mola et al. 2016; Zhang et al., 2019*).

Vacuum impregnation is a non-thermal method that allows the removal of gases and part of the native liquids of the treated product from the pores, and their replacement with an impregnation solution containing physiologically active compounds (minerals, vitamins, probiotics, prebiotics, antimicrobials, enzymatic anti-browning agents, pH reducing agents, phenolic compounds, natural dyes, etc.), without affecting the structural integrity of the food matrix (*Fito et al. 1994*). The process is carried out in two stages, as follows: the first stage consists of reducing the pressure to a certain vacuum level to remove gases from inside the pores; the second stage is represented by the restoration of atmospheric pressure to fill the pores with the chosen impregnation solution. The main theories underlying the description of the vacuum impregnation treatment process are represented by the hydrodynamic mechanism (HDM) and the deformation-relaxation phenomenon (DRP), the

main driving forces of the process being represented by the decrease in pressure and the subsequent return to atmospheric pressure (*Blanda et al., 2008*).

Vacuum impregnation has a wide applicability in the processing of food products with a porous structure, and can be used both to obtain functional food products (with additional health benefits) and to obtain fortified food products (with a role in preventing or correcting nutritional deficiencies).

RESULTS

Influence of the vacuum impregnation process on some properties of treated food products

Sensory modifications

Vacuum impregnation improves sensory characteristics by improving and/or preserving the color, volatile profile and taste of the final product. The process inhibits enzymatic browning by inhibiting the activity of polyphenol oxidase (PPO) and peroxidase (POD) (*An et al., 2019; Derossi et al., 2021*) and eliminates the bitter taste. In the case of dark-colored fruits, a small change in hue is observed, while in the case of light-colored fruits the color is well preserved (*Moreno et al., 2012*). The vacuum impregnation process is also effective in preserving the aromatic profile during the storage period, as demonstrated in the case of potatoes impregnated with rosemary oil (*Luo et al., 2019*). The process improves textural attributes, with the texture quality of the products being significantly related to the type of impregnation solutions used (*Xie and Zhao, 2003; Maltini et al., 1993*). Improvement of tissue structure and microstructural integrity can be achieved by impregnation of texture modifiers, such as calcium (*Moreno et al., 2012; Quiles et al., 2004*).

Thermal properties

The vacuum impregnation process improves thermal conductivity, glass transition temperature (Tg) and thermal diffusivity coefficient, which further enhances the stability of the product during storage (*de Lima et al., 2016; Song et al., 2017*). The process improves frost tolerance and mitigates frost damage by impregnating it with cryoprotectants (*Velickova et al., 2013*).

pH and water activity

The nature of the raw material, as well as the type and concentration of the impregnation solutions, affect the acidity of the product and the water activity, but in general, vacuum impregnation reduces the pH and water activity. The reduced pH further reduces the thermal resistance and growth rate of microorganisms, leading to microbial stability (*Derossi et al., 2013; Nawirska-Olszańska et al., 2020*). The reduced water activity in tissues leads to a decrease in the free water available for the development of microorganisms (*Radziejewska-Kubzdela et al., 2014*).

Industrial uses of vacuum impregnation in fruit and vegetable processing

Food fortification

Vacuum impregnation could be the best tool for food fortification processes. Food supplements, bioactive ingredients, such as vitamins and minerals, and other useful dissolved substances can be introduced into fruit and vegetable products without compromising their integrity using this technique (*Mavroudis et al., 1998*).

Enrichment with polyphenols and bioactive compounds

The content of bioactive compounds was increased in various types of fruits subjected to vacuum impregnation using a series of natural fruit juices as impregnation liquid. Approximately 20 polyphenolic compounds, including anthocyanins, flavonoids, phenolic acids, etc., were identified in these fruits (*Nawirska-Olszańska et al., 2020*).

Minimally processed foods

Minimally processed fruits and vegetables are products that retain the quality attributes of fresh produce. By using a suitable impregnation solution and rapidly changing the composition of the solid matrix, the vacuum impregnation process can help develop high-quality, stable minimally processed products (*Luo et al., 2019*).

Introduction of probiotics into fruits

Probiotics have been defined as live microbial food ingredients that have beneficial effects on human health by improving the microbial balance in the gut. This type of bacteria intended for human consumption usually belongs to the lactobacilli or bifidobacteria group (*Betoret et al., 2003*).

Pretreatment

Freezing is a conventional method of preserving fruits and vegetables. It retains nutrients better and improves the texture quality of the final product than other means of preservation. Vacuum impregnation with cryoprotectants (usually hypertonic sugar solution) or cryostabilizers (high-methoxyl pectin and glycerol) reduces the amount of freezable water, thus minimizing the loss of juice during thawing and also reducing cell wall damage due to ice crystals in frozen products (*Xie and Zhao, 2003; Martínez Monzó et al., 1998*).

The use of vacuum impregnation as a pretreatment before osmotic dehydration brings two major advantages: it reduces the moisture content before final drying to conserve energy and it incorporates dissolved functional substances, such as antimicrobial, antioxidant and anti-browning agents, to improve product quality (*Barat et al., 2001*).

Shelf life extension

By combining vacuum impregnation with various techniques and active agents, the shelf life of food products can be significantly extended. By partial removal of water, impregnation of organic acids to reduce pH, and incorporation of antimicrobial and antioxidant agents, along with storage at low temperatures, the shelf life of the product can be effectively extended (*Neri et al., 2016*).

Vacuum Impregnation Systems

Laboratory Model

The schematic diagram and image of a laboratory-scale vacuum impregnation system are shown in Fig. 1 and 2. As shown in Fig. 1, the temperature of the jacketed vacuum chamber is controlled by water from a thermostatic bath and monitored by T-type thermocouples connected to software. The pressure inside the chamber is reduced using a vacuum pump. This pump is connected to a proportional solenoid valve, coupled to a pressure transducer and to specialized software. The valve control and data collection are managed by this custom software. At the bottom of the tank, a centrifugal pump is connected to recirculate the solution and continuously stir the impregnation solution. The vapors created by the vacuum treatment are condensed in a tank filled with silica gel (*de Lima et al., 2016*).

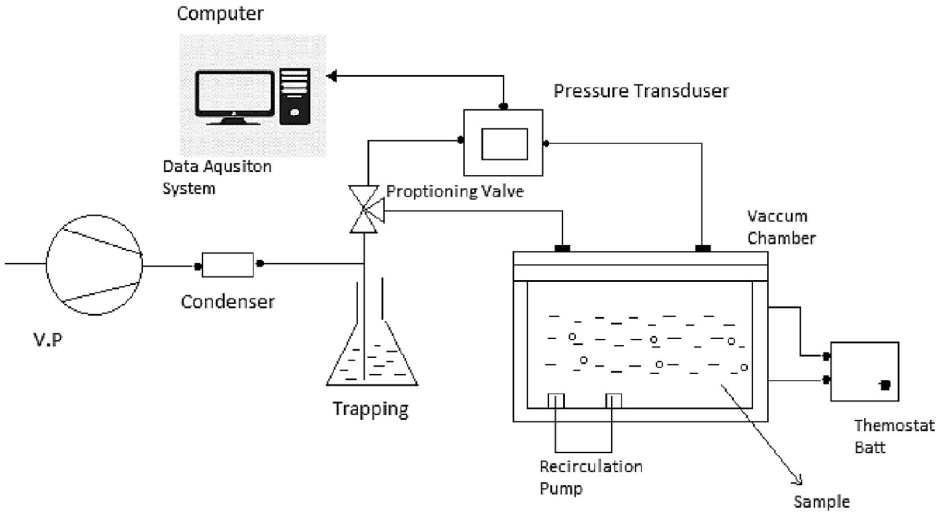

Fig. 1 – Schematic diagram of vacuum impregnation system (*de Lima et al., 2016*)

Fig. 2 – Laboratory scale vacuum impregnation set-up (*de Lima et al., 2016*)

Experimental model

As part of a national research program, INMA Bucharest developed an experimental model of a vacuum impregnation installation (fig. 3).

Fig. 3 - Experimental model of vacuum impregnation installation– IIV

The installation modifies the composition of porous food products by removing air and part of the internal liquids, followed by their impregnation with physiologically active compounds, without affecting the structural integrity of the food matrix, in order to improve the quality, nutritional content and extend the shelf life of the products. The installation is equipped with a pressure sensor for the atmosphere inside the impregnation vessel, two solenoid valves for controlling the air paths and a microcontroller, which allow the permanent monitoring and control of the process parameters. Depending on the solid:liquid ratio (between the mass of the solid sample and the volume of the impregnation liquid) usually chosen at a value of 1:10 or 1:5, the working capacity of the installation is 4 or 8 kg of product (distributed equally on the 4 trays arranged vertically on the installation rack) for a volume of impregnation liquid of 40 l.

The main technical characteristics of the IIV installation are highlighted below:

- Type of impregnation installation: vacuum impregnation;
- Construction: mobile platform type SKID;
- Volume of impregnation vessel: approx. 75 l;
- Wall thickness of impregnation vessel: 3 mm;
- Volume of impregnation liquid: approx. 40 l;
- Working capacity: 4 kg or 8 kg of product, depending on the working variant: solid:liquid ratio = 1:10 or 1:5 (mass of solid sample: volume of impregnation liquid);
- Vacuum obtaining method: vacuum pump, 2 stages, 0.37 kW electric motor, power supply at 220 Vac / 50 Hz, exhaust air flow 42 l/min, vacuum depth 15 µm col. Hg (2 Pa);
- Pressure sensor for vacuum: works in the range -1...0 bar (measuring range -1...3 bar), signal range 4...20 mA;
- Impregnation vessel cover: 15 mm thick transparent plexiglass, sealed with a 10 mm diam. gasket, FPM (Viton) material;
- Monitoring and control: automated process with the possibility of parameter adjustment.

CONCLUSIONS

The fresh-cut food market has experienced significant growth, especially in developed countries, due to consumer demands for healthy and nutritious food products with a fresh appearance.

The quality of fresh-cut fruits and vegetables is strongly affected by physiological changes such as enzymatic browning caused by tissue damage and high respiration rates, and by physical factors including mechanical damage and removal of the outer protection, which favors faster weight loss, shrinkage, loss of

color and appearance, and shortening of shelf life. Therefore, new innovative food processing technologies, such as immersion and vacuum impregnation techniques, are being investigated and implemented to preserve and improve the quality and extend the shelf life of these products.

As part of a national research program, INMA Bucharest developed an experimental model of a Vacuum Impregnation Installation that modifies the composition of porous food products by removing air and part of the internal liquids, followed by their impregnation with physiologically active compounds, without affecting the structural integrity of the food matrix, in order to improve the quality, nutritional content and extend the shelf life of the products.

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AGROBIOLOGICAL EVALUATION OF COMMON BEAN (*PHASEOLUS VULGARIS* L.) GENOTYPES UNDER THE SOIL AND CLIMATIC CONDITIONS OF CENTRAL MOLDOVA
/
CARACTERIZAREA AGROBIOLOGICĂ A UNOR GENOTIPURI DE FASOLE DE CÂMP (PHASEOLUS VULGARIS L.) ÎN CONDIȚIILE PEDOCLIMATICE ALE CENTRULUI MOLDOVEI

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ABSTRACT

Under the conditions of ARDS Secuieni, the agro-biological performance of five field bean genotypes (Phaseolus vulgaris L.) and the optimization of sowing density for this crop were studied. Two experiments were conducted: the first compared the genotypes, including the cultivars Delia and Doina and the local populations Secuieni, Moldoveni, and Lucăcești; the second evaluated the effect of sowing density (35, 45, 55, and 65 viable seeds/m²) using the cultivar Delia. The results showed significant differences among genotypes in terms of vegetative and reproductive traits, including plant height, number of pods and seeds per plant, seed weight, hectoliter mass, and 1000-seed weight. The Lucăcești population produced the highest seed yield (2741 kg/ha), while the cultivars Delia and Doina recorded lower yields. Sowing density had a major impact on growth and yield components: higher densities reduced the number of pods and seeds per plant, seed size, and total yield. The highest yield (2497 kg/ha) was obtained at the lowest density (35 seeds/m²), whereas the highest density (65 seeds/m²) caused a significant decrease in yield (1238 kg/ha). These results emphasize the importance of selecting adapted genotypes and optimizing sowing density to increase bean productivity under the pedoclimatic conditions of central Moldova.

REZUMAT

În condițiile SCDA Secuieni a fost studiată performanța agrobiologică a cinci genotipuri de fasole de câmp (Phaseolus vulgaris L.) și optimizarea densității de semănat la această cultură. S-au desfășurat două experiențe: prima a comparat genotipurile, incluzând soiurile Delia și Doina și populațiile locale Secuieni, Moldoveni și Lucăcești; a doua a analizat influența densității de semănat (35, 45, 55 și 65 semințe germinabile/m²) utilizând soiul Delia. Rezultatele au arătat diferențe semnificative între genotipuri în ceea ce privește trăsăturile vegetative și reproductive, incluzând înălțimea plantelor, numărul de păstăi și de boabe pe plantă, greutatea boabelor, masa hectolitrică și masa a 1000 de boabe. Populația Lucăcești a prezentat cea mai mare producție de boabe (2741 kg/ha), în timp ce soiurile Delia și Doina au înregistrat producții mai scăzute. Densitatea de semănat a avut un impact major asupra creșterii și componentelor producției: densitățile ridicate au redus numărul de păstăi și boabe pe plantă, dimensiunea semințelor și recolta totală. Cea mai mare producție (2497 kg/ha) s-a obținut la densitatea cea mai redusă (35 semințe/m²), în timp ce densitatea maximă (65 semințe/m²) a determinat o scădere semnificativă a recoltei (1238 kg/ha). Rezultatele obținute subliniază importanța selecției genotipurilor adaptate și a optimizării densității de semănat pentru creșterea productivității fasolei în condițiile pedoclimatice ale centrului Moldovei.

INTRODUCTION

Common bean (*Phaseolus vulgaris* L.) is among the most important grain legume crops worldwide, serving as a major source of plant-based protein for human nutrition (*Broughton, W. J., Hernández, G., Blair, M., et al., 2003; Gepts, P., Aragão, F. J. L., de Barros, E., et al., 2008*). Due to its high content of proteins, complex carbohydrates, dietary fiber, vitamins, and essential minerals, common bean plays a vital role in food security, particularly in developing and transitional regions with limited access to animal protein (*Messina, V., 2014; FAO, 2019*). Beyond its nutritional value, *Phaseolus vulgaris* L. contributes to sustainable agricultural systems by enhancing soil fertility through biological nitrogen fixation in symbiosis with Rhizobium spp., thereby reducing the need for mineral fertilizers. Its inclusion in crop rotations also promotes agroecosystem diversity

and environmentally friendly farming practices (*Graham, P. H., & Vance, C. P., 2003; Peoples, M. B., Brockwell, J., Herridge, D. F., et al., 2009; Singh, S. P., 2007*). A study conducted at ARDS Secuieni demonstrated that common bean not only improves soil fertility but can also generate substantial economic returns under local pedoclimatic conditions, underscoring the benefits of expanding dwarf field bean cultivation in Central Moldova (*Isticioaia, S. F., Leonte, A., Pintilie, A. S., et al., 2025*).

The productivity and yield stability of common bean are strongly influenced by the interaction between genotype, environmental conditions, and crop management practices (*Singh, S. P., 2007; Beebe, S. E., Rao, I. M., Blair, M. W., & Acosta-Gallegos, J. A., 2013*). Climate variability, including drought stress, elevated temperatures, and uneven rainfall distribution, represents a significant constraint for common bean production, highlighting the need to select well-adapted genotypes (*Rosales, M. A., Ocampo, E., Rodríguez-Valentín, R., et al., 2012; Asfaw, A., Blair, M. W., & Almekinders, C., 2009*). Substantial genetic variability exists among bean genotypes in terms of growth habit, phenological development, stress tolerance, and yield components such as pod number, seed number per pod, and thousand-seed weight (*Acosta-Gallegos, J. A., & White, J. W., 1995; Blair, M. W., Díaz, L. M., Buendía, H. F., & Duque, M. C., 2009*). Accordingly, agrobiological evaluation under specific soil and climatic conditions is essential for identifying cultivars with high productivity and stable performance across environments (*Beebe, S. E., Rao, I. M., Devi, M.J., Polanía, J., 2014*). In southeastern Romania, over 450 common bean lines were assessed at INCDA Fundulea to characterize phenotypic traits and evaluate the effects of cross-pollination on quantitative and qualitative seed parameters (*Teodorescu, E., Barcanu, E., Agapie, O., Gherase, I., & Mirea, E., 2025*). Moreover, numerous studies on the Romanian common bean cultivar Doina have been conducted at VRDS Buzău, with the main objective of optimizing cultivation technology and improving crop protection strategies (*Mirea, E., Burnichi, F., Toader, A. et al, 2021*).

Among agronomic factors, planting density is a key determinant of plant architecture, light interception, competition for water and nutrients, and microclimatic conditions within the crop canopy (*Board, J. E., Kamal, M., & Harville, B. G., 1992; Egli, D. B., 2013*). Both excessively low and excessively high densities can limit yield due to inefficient resource use or intensified inter-plant competition (*Silveira, P.M., Nascente, A.S., Silva, J.G., 2018*). The response of common bean to sowing density is genotype-dependent and influenced by growth type, environmental conditions, and soil fertility (*Mabrouk, Y., Mejri, S., Hemissi, I., et al., 2018*). Optimizing sowing density in relation to genotype characteristics is therefore critical to maximize yield potential and ensure production stability.

In this context, the present study aimed to evaluate the agrobiological performance of common bean genotypes under the soil and climatic conditions of Central Moldova (ARDS Secuieni), with particular emphasis on yield-related traits and the effects of sowing density. The findings are expected to support the identification of well-adapted genotypes and to inform cultivation practices for improving field bean productivity in the region.

MATERIALS AND METHODS

To achieve the research objectives, two field experiments were conducted at the ARDS Secuieni experimental station.

The first experiment included two common bean varieties (Phaseolus vulgaris L.), namely Delia and Doina, and three cultivars/populations: Secuieni, Moldoveni, and Lucăcești. The experiment was arranged in the field using a randomized block design with three replications.

In order to optimize the cultivation technology of common bean, a second experiment was established in which for sowing densities were tested: 35, 45, 55 and 65 germinable seeds per square meter. These were applied at sowing, using the variety Delia.

Primary soil tillage and seedbed preparation were carried out following the bean cultivation technology recommended for the conditions of the ARDS Secuieni area. For seedbed preparation, 200 kg/ha of a complex fertilizer (N_{15}:P_{15}:K_{15}) was applied, and on the day of sowing, soil working was performed using a vibromix. The preceding crop was winter wheat. Sowing was done manually on 16 May 2025, with a row spacing of 50 cm and a plot area of 10 m².

The experimental field at ARDS Secuieni is located on the second terrace of the Siret River, on a typical cambic faeoziom (chernozem) soil, characterized according to the data listed in Table 1.

Table 1

Physico-chemical properties of the soil in the common bean experimental field

Soil Property	Value
Nitrogen supply	Medium (N: 2.7)
Phosphorus supply	Very well supplied; very good availability (PAL: 131.3 mg/kg soil)
Corrected phosphorus availability	106.7 mg/kg soil
Potassium supply	Very well supplied (KAL: 208.3 mg/kg soil)
Magnesium supply	Well supplied (Available Mg: 147.2 mg/kg soil)
Sulfur supply	Well supplied (Available S: 20.5 mg/kg soil)
Iron and copper supply	Well supplied (Fe: 50.7 mg/kg soil, Cu: 3.1 mg/kg soil)
Manganese, zinc, organic carbon, humus	Medium supply (Mn: 18.4 mg/kg soil, Zn: 2.5 mg/kg soil, Organic C: 1.62%, Total humus: 2.79%)
Boron and molybdenum supply	Poorly supplied (B: 19.5 µg/kg soil, Mo: 6.2 mg/kg soil)
Soil reaction (pH)	Neutral (pH H_2O: 7.20)
Soil salinity	Non-salinized (Electrical conductivity H_2O: 144.8 µS/cm; 50.7 mg/100 g soil)

In the 2025 agricultural year, the climatic conditions at ARDS Secuieni were slightly warmer than the multiannual average, with significant seasonal temperature variability. This uneven thermal regime directly influenced the physiological processes of common bean (*Phaseolus vulgaris*), affecting germination, vegetative growth, and pod formation. The previous autumn was thermally balanced, favoring soil preparation. Winter 2024–2025 recorded positive deviations, promoting early biological activity in spring. March was particularly warm (+4.6 °C), accelerating soil thaw, while April was near normal. May, critical for germination and early vegetative growth, was cooler (–2.4 °C), delaying emergence and uniformity. Summer temperatures were generally favorable, with moderate positive deviations in July (+1.9 °C) and August (+1.1 °C), supporting growth and pod development. Overall, the annual deviation was +0.5 °C, with uneven distribution influencing growth dynamics (Fig. 1).

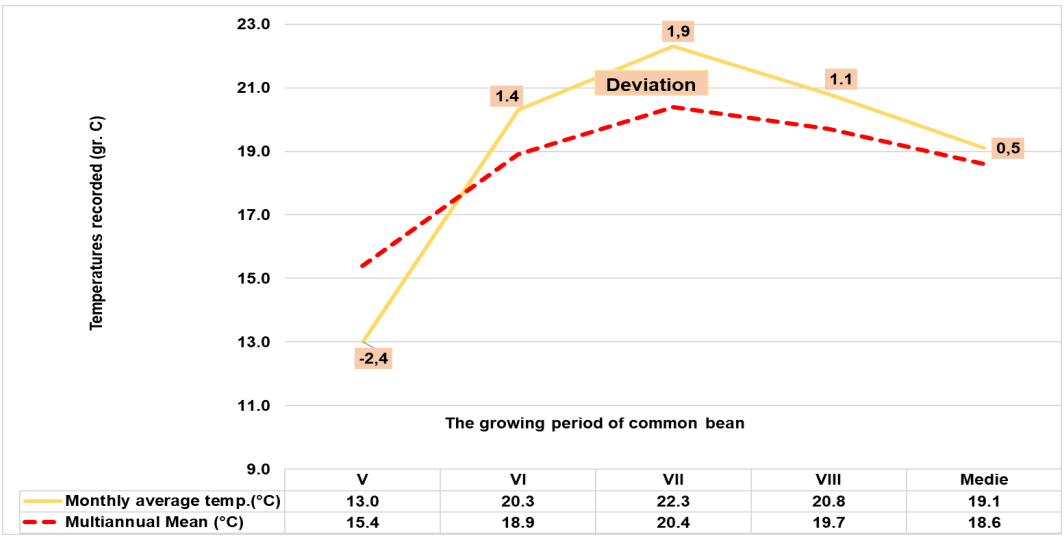

Fig. 1 - Temperatures recorded during the growing season of common bean in 2025 at ARDS Secuieni

The 2024–2025 agricultural year was also marked by an uneven precipitation regime. From October to January, rainfall was near the multiannual average, while February was dry, reducing soil water reserves. March returned to normal rainfall, favoring field preparation. During the bean growing season, total rainfall was 201.2 mm, well below the multiannual mean of 287.6 mm (–86.4 mm), negatively affecting growth. May was excessively rainy (116.4 mm; +52.1 mm), but this did not compensate for earlier deficits, resulting in alternating drought and water excess. Summer rainfall was insufficient, with deficits in June (–76.5 mm), July (–7.4 mm), and August (–49.4 mm), reducing soil moisture during critical pod formation and seed-filling stages. Overall, the precipitation regime was characterized by a pronounced water deficit and uneven distribution, which adversely affected physiological processes and bean productivity (Fig. 2).

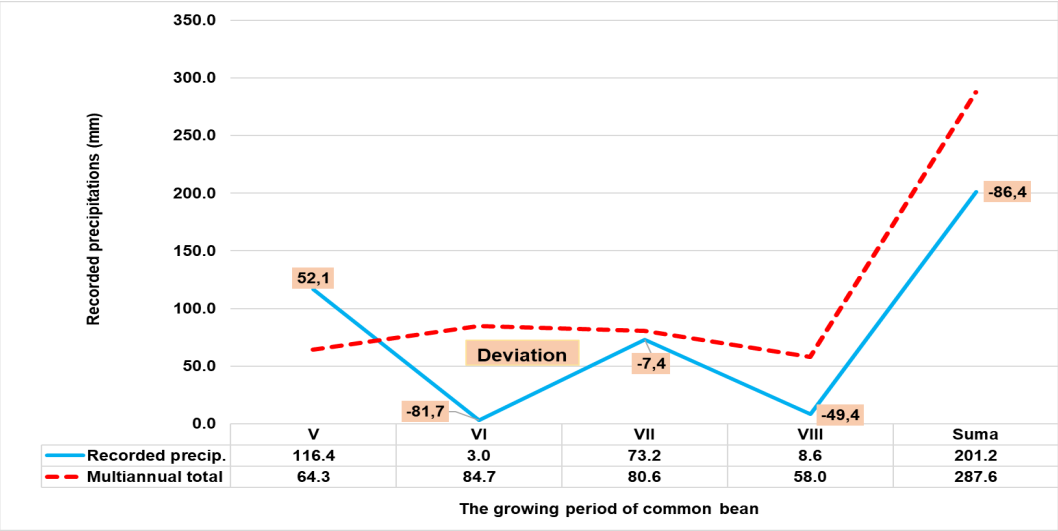

Fig. 2 - Precipitations recorded during the growing season of common bean in 2025 at ARDS Secuieni

RESULTS

a) Results on the Influence of genotype on the growth and development of field bean

The growth and development of the experimental bean genotypes were significantly influenced by their genetic characteristics. Observations of vegetative and reproductive traits, including plant height, pod number, seed number per pod, and seed weight, revealed marked differences between cultivars and local populations. Early vegetative stages, such as the appearance of the second true leaf, varied among genotypes, while the timing of flowering and maturity showed clear genotypic patterns. These variations were also reflected in biometric measurements at maturity, indicating that genotype plays a decisive role in both growth dynamics and yield potential under the experimental conditions.

In the phenological analysis of the studied common bean genotypes, the appearance of the second true leaf occurred between June 5 and June 7, with the earliest observed in the Delia and Secuieni genotypes (June 5) and the latest in Doina (June 7). All genotypes exhibited intensely green leaves and an erect stem habit, characteristics indicative of uniform vegetative development and favorable for mechanized harvesting (Table 2).

Inflorescence appearance was recorded between June 25 and July 7, while the onset of flowering occurred between June 26 and July 7. The Delia cultivar, Doina, and Lucăcești population started flowering around June 26–July 1, whereas Secuieni and Moldoveni populations flowered slightly later (July 1–7). The number of days from emergence to flowering ranged from 49 to 56 days, reflecting a rapid initial vegetative cycle across all genotypes (Table 2).

Table 2

Observations and measurements conducted up to the flowering stage for the experimental genotypes

No.	Genotype	Date of 2nd true leaf appearance	Leaf color	Stem habit	Date of inflorescence appearance	Start of flowering [date]	End of flowering [date]	Days from emergence to flowering
1	Doina	07.06	Green	Erect	26.06	01.07	26.07	49
2	Delia	05.06	Green	Erect	26.06	01.07	24.07	49
3	Secuieni pop.	05.06	Green	Erect	01.07	07.07	01.08	56
4	Moldoveni pop.	06.06	Green	Erect	01.07	01.07	02.08	56
5	Lucăcești pop.	06.06	Green	Erect	25.06	01.07	26.07	56

Overall, these results indicate that the studied genotypes display uniform vegetative growth, while the observed differences in flowering timing may be relevant for selecting genotypes with a shorter growth cycle or better adaptation to local cultivation conditions.

The observations and measurements recorded at maturity for the experimental bean genotypes reveal notable differences in plant architecture and phenology. Plant height varied considerably among the genotypes, ranging from 24.2 cm in Doina to 39.6 cm in the Secuieni population, with Delia, Moldoveni, and Lucăcești showing intermediate heights of 30.2–36.3 cm. The height of first pod insertion also differed, from

12.5–12.6 cm in Secuieni and Doina to 18.5 cm in Delia, indicating variation in canopy structure and potential suitability for mechanized harvesting (Table 3).

The onset of maturity occurred between August 10 and August 15, with Doina and Delia reaching maturity earliest (10 August), followed by Secuieni (12 August), and Moldoveni and Lucăcești maturing last (15 August). The end of maturity ranged from 18 to 22 August. The vegetation period was generally 90 days for most genotypes, except for Lucăcești, which exhibited a slightly longer cycle of 95 days. Harvest dates followed shortly after the end of maturity, ranging from 14 to 26 August (Table 3).

Overall, these results indicate that the studied genotypes exhibit variation in plant height and pod insertion, which may influence light interception, plant density, and mechanized harvesting efficiency. Additionally, differences in maturity timing suggest potential for selecting genotypes with a shorter growth cycle or better adaptation to local growing conditions.

Table 3

Observations and measurements at maturity for the experimental genotypes

No.	Genotype	Plant height	Height of first pod insertion	Beginning of maturity	End of maturity	Vegetation period	Harvest date
		[cm]	[cm]	[date]	[date]	[days]	[date]
1	Doina	24.2	12.6	10.08	18.08	90	26.08
2	Delia	30.4	18.5	10.08	18.08	90	26.08
3	Secuieni pop.	39.6	12.5	12.08	20.08	90	14.08
4	Moldoveni pop.	30.2	14.3	15.08	20.08	90	20.08
5	Lucăcești pop.	36.3	15.4	15.08	22.08	95	25.08

The biometric evaluation of the field bean genotypes revealed significant differences in pod and seed characteristics, as well as in seed yield per plant. The number of pods per plant varied from 2 to 4, with Doina and Lucăcești producing the highest number of pods (4 pods per plant), while the Secuieni and Moldoveni populations produced only 2 pods per plant. The number of seeds per pod ranged from 3 to 6, with Delia and Lucăcești exhibiting the highest seed number per pod (6 seeds), and Secuieni the lowest (3 seeds) (Table 4).

Seed weight per plant also differed notably among genotypes. Lucăcești recorded the highest seed weight (8.6 g), followed by Doina (5.4 g) and Delia (4.7 g), while Secuieni and Moldoveni had lower values of 3.6 g and 3.9 g, respectively. Hectoliter weight (HW) varied between 62 and 87 kg/hl, with Delia exhibiting the highest HW (87 kg/hl) and Secuieni the lowest (62 kg/hl). Thousand-seed weight (TSW) ranged from 232.6 g in Delia to 363.8 g in Lucăcești, indicating substantial differences in seed size and mass among the genotypes (Table 4).

Table 4

Biometric measurements of field bean genotypes

No.	Genotype	Pods per plant	Seeds per pod	Seed weight per plant	HW	TSW
		[no.]	[no]	[g]	[kg/hl]	[g]
1	Doina	4	5	5.4	68	304.2
2	Delia	3	6	4.7	87	232.6
3	Secuieni pop.	2	3	3.6	62	238.6
4	Moldoveni pop.	2	5	3.9	68	312.5
5	Lucăcești pop.	4	6	8.6	63	363.8

Overall, the results suggest that Lucăcești combines both a relatively high number of pods and larger seeds, leading to the highest seed weight per plant, while Secuieni produces fewer pods and lighter seeds. The variation in HW and TSW among genotypes reflects genetic differences in seed quality traits, which may be valuable for breeding programs targeting yield improvement and adaptation to local conditions.

The seed yield of the experimental bean genotypes evaluated at ARDS Secuieni in 2025 showed significant differences among the tested varieties and populations. The highest yield was recorded in the Lucăcești population (2741 kg/ha), representing 153% of the control mean and 955 kg/ha (53%) above the mean, a difference that was highly significant (***) (Table 5).

Intermediate yields were observed for Moldoveni (1800 kg/ha, 101% of the mean) and Secuieni population (1638 kg/ha, 92% of the mean), both close to the mean control value (1786 kg/ha) and showing minimal deviations (+14 kg/ha for Moldoveni, -148 kg/ha for Secuieni) (Table 5).

Lower yields were recorded for Doina (1497 kg/ha, 84% of the mean) and Delia (1252 kg/ha, 70% of the mean). These differences were negative and statistically significant, with Doina showing a distinct significant decrease (oo, -289 kg/ha, -16%) and Delia exhibiting a highly significant reduction (ooo, -534 kg/ha, -30%) (Table 5).

Table 5

Seed yield of bean genotypes, ARDS Secuieni – 2025

No.	Genotype	Yield		Difference from Mean (Control)		Significance *
		[kg/ha]	[%]	[kg/ha]	[%]	
1	Doina	1497	84	-289	-16	oo
2	Delia	1252	70	-534	-30	ooo
3	Secuieni pop.	1638	92	-148	-8	
4	Moldoveni pop.	1800	101	14	1	
5	Lucăcești pop.	2741	153	955	53	***
6	Mean – Control	1786	100	Ctr.	Ctr.	
LSD (kg/ha): 5% = 204; 1% = 289; 0.1% = 419						

oo → the difference from the control is negative and statistically distinct significant; ooo → the difference from the control is negative and highly significant; * → the difference from the control is positive and highly significant*

Overall, these results demonstrate that the Lucăcești population is the most productive genotype under the 2025 experimental conditions, whereas Delia and Doina are less productive. The observed differences were statistically confirmed by the LSD values (5% = 204 kg/ha; 1% = 289 kg/ha; 0.1% = 419 kg/ha), highlighting the significant effect of genotype on seed yield.

b) Results on the Influence of sowing density on the growth and development of field bean

Bean performance was poor at high sowing densities at ARDS Secuieni, with overcrowding clearly reducing growth and yield.

The influence of sowing density on the growth and yield components of bush-type field bean was clearly observed. As sowing density increased from 35 to 65 germinable seeds/m², the number of pods per plant decreased from 52.4 to 22.2, and the total number of seeds per plant declined from 267.2 to 77.7. Additionally, the number of seeds per pod decreased from 5.1 to 3.5, and the thousand-seed weight (TSW) declined from 282.5 g to 222.1 g (Table 6).

Table 6

Effect of Sowing Density on Yield Components of Bean

No.	Variant	Plant density at emergence	Number of pods per plant	Number of seeds per plant	Number of seeds per pod	TSW
	[no. of germinable seeds/m²]	[plants/m²]	[no.]	[no.]	[no.]	[g]
1	35	32	52.4	267.2	5.1	282.5
2	45	41	44.0	184.8	4.2	268.9
3	55	49	30.4	115.5	3.8	243.2
4	65	59	22.2	77.7	3.5	222.1

These results indicate that higher plant density negatively affected both vegetative growth and individual reproductive performance, likely due to competition for light, nutrients, and space.

Conversely, lower sowing densities allowed plants to develop more pods, produce more seeds per plant, and maintain higher seed weight, demonstrating superior individual plant performance. The observed trends are consistent with known responses of bush-type common bean to plant population, highlighting the importance of optimizing sowing density to balance per-plant productivity with overall field yield.

The seed yield of bush-type bean was significantly influenced by sowing density under the 2025 experimental conditions at ARDS Secuieni. The highest yield was recorded at the lowest sowing density of 35 germinable seeds/m², reaching 2497 kg/ha, which represents 136% of the control mean and 658 kg/ha (+36%) above the mean, a difference that was positively and distinct significantly different (**) (Table 7).

As sowing density increased, yield progressively decreased. At 45 seeds/m², yield was 2068 kg/ha (112% of the mean), showing a small, non-significant increase over the mean. Further increases in density

led to reduced yields: 1552 kg/ha (84% of the mean) at 55 seeds/m² and 1238 kg/ha (67% of the mean) at 65 seeds/m². The highest density (65 seeds/m²) resulted in a significant negative distinct difference from the control (-601 kg/ha, -33%), indicating that overcrowding severely reduced productivity (Table 7).

Table 7

Seed yields of bean as influenced by sowing density, ARDS Secuieni – 2025

No.	Variant	Yield		Difference from Mean (Control)		Significance *
	[no. of germinable seeds/m²]	[kg/ha]	[%]	[kg/ha]	[%]	
1	35	2497	136	658	36	**
2	45	2068	112	229	12	
3	55	1552	84	-287	-16	
4	65	1238	67	-601	-33	oo
5	Mean – Control	1839	100	Ctr.	0	
LSD (kg/ha): 5% = 478; 1% = 289; 0.1% = 691						

**oo → the difference from the control is negative and statistically distinct significant; ** → the difference from the control is positive and distinct significant*

Overall, these results demonstrate a clear negative effect of high plant density on bean yield, while lower sowing densities promote higher seed production per unit area. The trends are consistent with the observed reductions in pod number, seed number per plant, and thousand-seed weight at higher densities. The differences were statistically validated by LSD values (5% = 478 kg/ha; 1% = 289 kg/ha; 0.1% = 691 kg/ha), confirming the significant impact of sowing density on yield.

CONCLUSIONS

The evaluated bean genotypes showed clear differences in vegetative growth, phenological development, and yield components. Lucăcești population combined a relatively high number of pods with larger seeds, resulting in the highest seed yield, whereas Delia and Doina were less productive.

Plant height, pod insertion height, and maturity timing varied among genotypes, which may influence canopy architecture, light interception, and mechanized harvesting efficiency.

High sowing densities negatively affected bean growth and yield, reducing the number of pods and seeds per plant, seeds per pod, and thousand-seed weight. The highest density (65 seeds/m²) led to the lowest yield, highlighting the negative impact of overcrowding.

Lower sowing densities (35–45 seeds/m²) favored individual plant performance and resulted in higher total yields, demonstrating the importance of optimizing planting density according to genotype characteristics.

Overall, the study emphasizes the need to select well-adapted genotypes and appropriate sowing densities to maximize productivity and ensure stable bean yields under the soil and climatic conditions of Central Moldova.

ACKNOWLEDGEMENTS

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STUDY ON THE PRODUCTIVITY AND ECONOMIC EFFICIENCY OF WINTER BARLEY UNDER THE PEDOCLIMATIC CONDITIONS OF CENTRAL MOLDOVA

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STUDIU PRIVIND PRODUCTIVITATEA ȘI EFICIENȚA ECONOMICĂ A ORZULUI DE TOAMNĂ ÎN CONDIȚIILE PEDOCLIMATICE ALE CENTRULUI MOLDOVEI

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Keywords: *agricultural sustainability; economic efficiency; winter barley; yield components*

ABSTRACT

The paper presents the results obtained between 2023 and 2025 at ARDS Secuieni regarding the productivity and economic efficiency of several winter barley varieties. Twelve barley varieties were evaluated (10 six-row varieties and 2 two-row varieties), and the results revealed significant differences among varieties in terms of plant height, number of spikes/m², number of grains per spike, grain weight, and thousand-grain weight. The most productive varieties were Cadril, Azur FD, and Artemis, with average yields ranging from 7,483 to 8,105 kg/ha, while the varieties Ileana and Iulian recorded the lowest yields (5,160–5,920 kg/ha). Economic analysis showed that high-yielding varieties also generated the highest net profits, exceeding 3,000 lei/ha, whereas lower-yielding varieties incurred higher production costs per kilogram and correspondingly lower profits (1,461–1,978 lei/ha). The experimental period was characterized by higher temperatures (+2.2°C) and reduced precipitation (-84.4 mm) compared to the multi-annual average, highlighting the resilience of well-adapted varieties. The study emphasizes the importance of selecting varieties suited to local conditions to maximize both yield and economic efficiency of winter barley cultivation in central Moldova.

REZUMAT

Lucrarea prezintă rezultatele obținute în perioada 2023–2025 la SCDA Secuieni privind productivitatea și eficiența economică a unor soiuri de orz de toamnă. Au fost evaluate 12 soiuri de orz (10 soiuri cu 6 rânduri și 2 soiuri cu 2 rânduri), iar rezultatele au evidențiat diferențe semnificative între soiuri în ceea ce privește înălțimea plantelor, numărul de spice/m², numărul de boabe/spic, greutatea boabelor și masa a 1000 de boabe. Cele mai productive soiuri au fost Cadril, Azur FD și Artemis, cu recolte medii între 7.483 și 8.105 kg/ha, în timp ce soiurile Ileana și Iulian au înregistrat cele mai mici recolte (5.160–5.920 kg/ha). Analiza economică a arătat că soiurile cu producții ridicate au generat și cele mai mari profituri nete, depășind 3.000 lei/ha, în timp ce soiurile mai puțin productive au avut costuri de producție mai mari pe kilogram și profituri mai mici (1.461–1.978 lei/ha). Perioada experimentală a fost caracterizată de temperaturi mai ridicate (+2,2°C) și precipitații reduse (-84,4 mm) față de media multianuală, evidențiind reziliența soiurilor adaptate. Studiul subliniază importanța selecției soiurilor adaptate la condițiile locale pentru maximizarea producției și a eficienței economice a culturii de orz de toamnă în centrul Moldovei.

INTRODUCTION

Barley (*Hordeum vulgare* L.) is among the earliest and most fundamental cereal crops domesticated by humans, with a history of approximately 10,500 years, marking the transition to organized agriculture and the development of complex food systems (*Soleimani, S., Wichmann, P., Pillen, K. et al., 2025; Mascher, M., Schuenemannm, V. J., Davidovich, U., et al., 2016*). This globally significant cereal is distinguished by its high adaptability to environmental variability and the versatility of its economic applications, including food and feed production, brewing and distillation industries, and its strategic role in agro-food value chains (*Alionte, E.G., 2006; FAO, 2020*).

The remarkable stability of barley yields places it among the most reliable crops under conditions of climatic stress, providing a critical source of food security during droughts or unexpected temperature fluctuations (*Lakew, B., Gebre, H., Alemayehu, F., 1996*). Its short growing season, coupled with ecological

plasticity, facilitates widespread adoption by farmers seeking consistent and economically viable production even under suboptimal pedoclimatic conditions (*Tarawneh, M., Al-Jaafreh, A. M., Al-Dal'in, H., et al., 2021; Niță, S., Imbrea, I. M., Niță, L. D. et al., 2025*). In Romania, barley holds a strategic position within the agricultural sector, cultivated for both domestic consumption and export, with areas ranging from 447,000 to 629,230 ha during 2023–2025, driven by sustained demand from the malting and livestock industries (*Cristea, R.M., Gradilă, M., Jalobă, D. et al., 2024; Eurostat, 2025*).

The productivity of winter barley arises from a complex interaction between genetic factors, pedoclimatic characteristics, and technological practices. In the context of global climate change, this interdependence becomes critical for guiding agricultural decisions that directly impact yield, profitability, and crop sustainability (*Popescu, A., Dumitru, M., & Stan, G., 2019; Ionescu, L., Marinescu, D., 2021*). According to recent studies conducted at NARDI Fundulea on 10 winter two-rowed barley genotypes, the efficiency of nitrogen fertilization influences the quality parameters of seeds required for malting, but it did not cause significant differences in yield between fertilized and unfertilized plots (*Petcu, E., Vasilescu, L., Ion, V., 2025*).

The Central Moldavian region, characterized by high pedoclimatic variability, predominantly chernozem soils, and uneven rainfall distribution, necessitates carefully calibrated cultivation strategies aimed at maximizing yield while minimizing economic risks (*Leonte, A., Pintilie, S., Popa, D., Naie, M., 2023*).

Genotypic responses to water stress vary significantly, influencing both early growth and subsequent development, while certain varieties demonstrate resilience, recovering grain yield following rehydration, thereby providing a competitive advantage in climate-sensitive agricultural systems (*Reynolds, M., Tuberosa, R., 2008*). The analysis of Romanian barley cultivars released between 1959 and 2019 showed that grain morphometry depends on the environment, cultivar, and their interaction, highlighting high trait diversity and a slight reduction in phenotypic variation in modern germplasm (Vasilescu, L., Petcu, E., Sîrbu, E., Petcu, E., Lazăr, C., 2022).

The study conducted at ARDS Secuieni between 2023 and 2025 aimed to identify genotypes with superior adaptation potential to the specific conditions of Central Moldavia, while simultaneously assessing the influence of variety on yield, input costs, market price, and economic efficiency, thereby generating critical insights for optimizing technological selection and strategic crop management.

MATERIALS AND METHODS

The study was conducted at the Agricultural Research and Development Station (ARDS) Secuieni, with the aim of evaluating the performance of Romanian winter barley varieties under the pedoclimatic conditions of Central Moldova. The experimental material consisted of 12 cultivars, including ten six-row varieties and two two-row varieties. The trials were established in comparative competition plots, using a randomized block design with three replications, without repeating the base scheme. Each experimental unit had a harvestable area of 10 m².

The experimental field, on the second terrace of the Siret River, has a typical cambic chernozem (phaeozem) soil. It is moderately supplied with nitrogen, very well supplied with phosphorus and potassium, well supplied with magnesium and sulfur, and has generally adequate micronutrients. Manganese, zinc, organic carbon, and humus are at medium levels, while boron and molybdenum are low. The soil is neutral (pH 7.20) and non-saline (Table 1).

Table 1

Physico-chemical properties of the soil in the common bean experimental field

Soil Property	Value
Nitrogen supply - medium	IN = 2.7
Phosphorus supply - very good availability	PAL = 131.3 mg/kg soil; corrected PAL = 106.7 mg/kg soil
Potassium supply - very good:	KAL = 208.3 mg/kg soil
Magnesium supply - well supplied	Assim. Mg = 147.2 mg/kg soil
Sulfur supply - well supplied	Well supplied: Mobile S = 20.5 mg/kg soil
Iron and copper supply - well supplied	Well supplied: Fe = 50.7 mg/kg; Cu = 3.1 mg/kg
Manganese, zinc, organic carbon, humus - medium	Mn = 18.4 mg/kg; Zn = 2.5 mg/kg; C org. = 1.62%; Total humus = 2.79%
Boron and molybdenum - poorly supplied	B = 19.5 µg/kg; Mo index = 6.2
Soil pH - Neutral	pH water = 7.20
Salinity - Non-saline	CEH2O = 144.8 µS/cm; 50.7 mg/100 g soil

The experimental period 2023–2025 was characterized by less favorable climatic conditions for winter barley. On average, over the three years, deviations from the multi-annual mean temperature ranged between -0.7°C (May) and +4.5°C (January), with a significant increase in temperature during the growing season of approximately 2.2°C (Fig. 1).

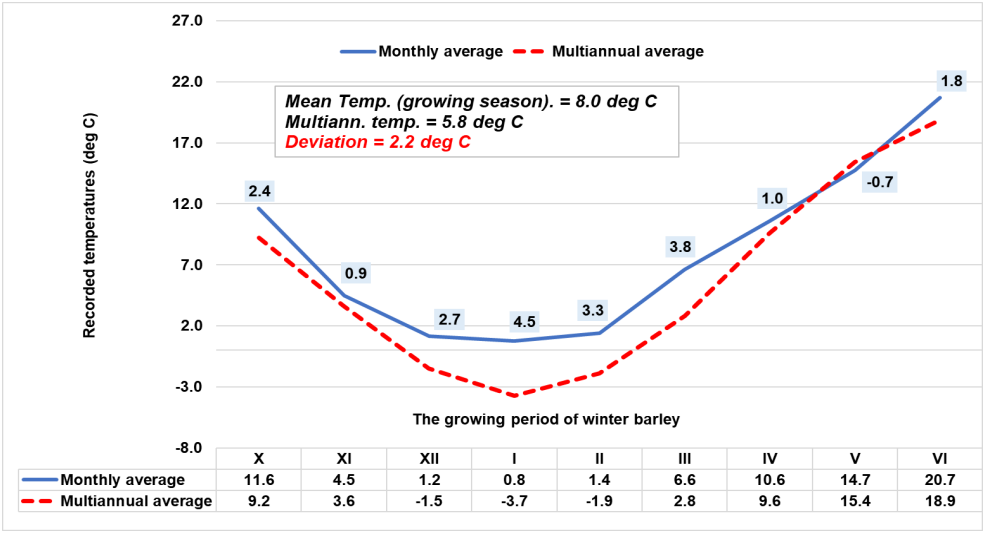

Fig. 1 - Temperatures recorded at ARDS Secuieni during the growing season of winter barley, average 2023–2025, ARDS Secuieni

Regarding precipitation, over the entire growing season of wheat (from sowing to physiological maturity), deviations from the multi-annual average ranged between -45.6 mm (June) and +0.6 mm (March). Analyzing the total annual precipitation compared to the multi-annual average, the period under study was characterized as excessively dry, with a total deviation of -84.4 mm. This indicates a decrease in precipitation during the wheat growing season by approximately 25% (Fig. 2).

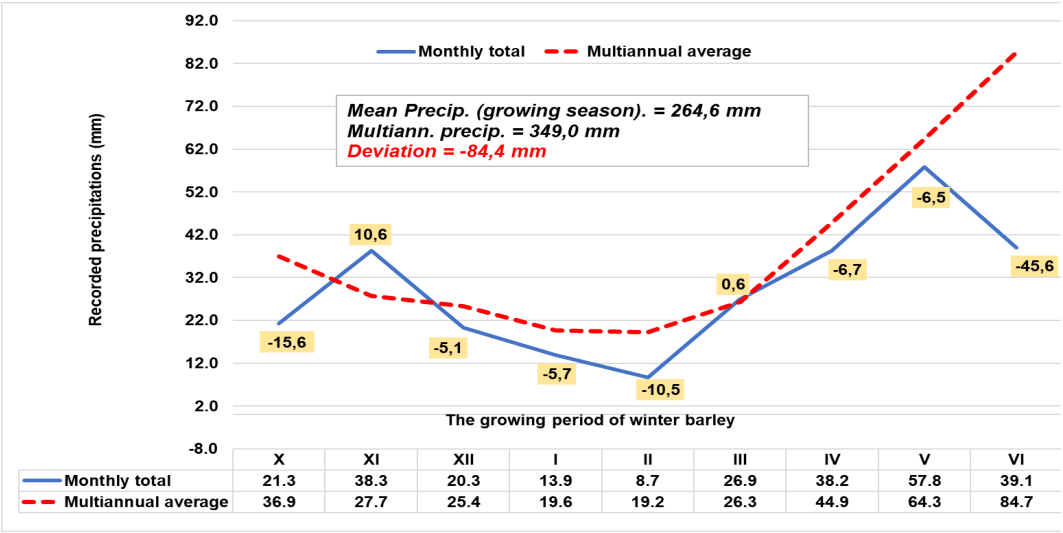

Fig. 2 - Temperatures recorded at ARDS Secuieni during the growing season of winter barley, average 2023–2025

The applied cultivation technology followed the standard recommendations for winter barley in the conditions of Central Moldova. Sowing was performed during the optimal period for the study area, between October 15 and October 20. Crop management practices, including soil preparation, fertilization, and plant protection, were carried out uniformly across all experimental variants in order to minimize non-experimental sources of variation.

Data analysis was performed using analysis of variance (ANOVA) to assess the effects of genotype on the studied traits. Differences among means were interpreted based on statistical significance thresholds, allowing for an objective evaluation of varietal performance under the given environmental conditions.

RESULTS

The plant height of barley exhibited substantial variation among the varieties analyzed, reflecting the strong influence of genetic factors on this agronomic trait. Among the studied genotypes, the tallest plants were recorded in the six-row barley variety Cardinal, which reached an average height of 107.9 cm, followed closely by the two-row variety Ileana, with an average height of 106 cm. In contrast, the Gabriela variety, also a two-row type, displayed the shortest stature, highlighting a pronounced difference in growth habit even within varieties of the same row-type classification.

These differences in plant height are largely determined by the genetic characteristics inherent to each variety, although environmental conditions and cultivation practices may also modulate growth to a certain extent. Understanding such variability is crucial for barley breeding programs, as plant height can influence key factors such as lodging susceptibility, light interception, and overall biomass production. The results indicate that selection of varieties with optimal height can contribute to improved crop performance and yield stability.

Moreover, the observed variation suggests potential for targeted breeding strategies, where taller varieties like Cardinal may be advantageous in regions or systems where higher biomass is desirable, whereas shorter varieties like Gabriela could be preferred in environments prone to strong winds or where reduced lodging risk is critical. Overall, these findings underscore the importance of genotype-specific evaluation in barley cultivation to optimize both agronomic performance and resource use efficiency (Fig. 3).

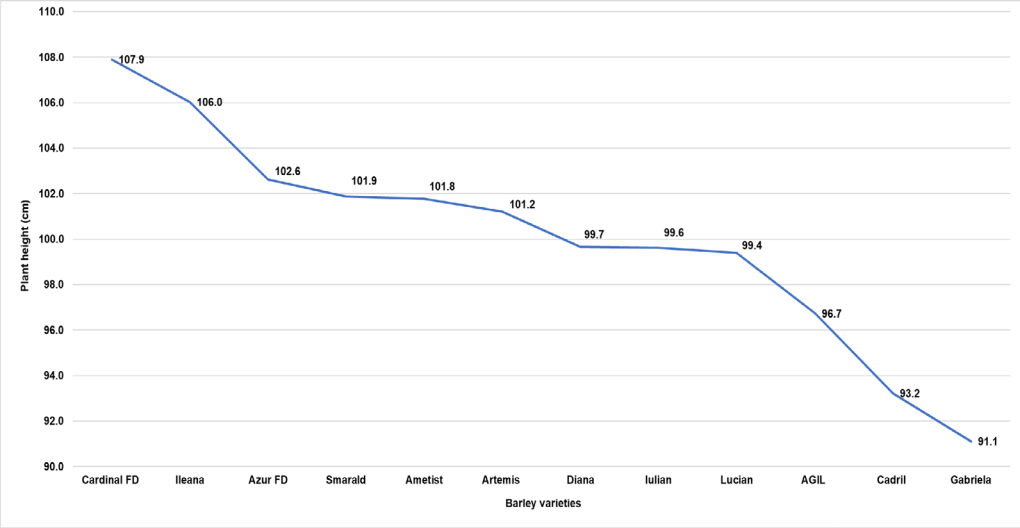

Fig. 3 - Plant height in winter barley, average 2023 - 2025 (original data)

The data presented in Figure 4 demonstrate that the number of spikes in winter barley was significantly influenced by the variety. Among the varieties analyzed, Diana, Ileana, and Gabriela exhibited the highest spike densities, exceeding 800 spikes/m², which reflects their strong tillering capacity and potential for high yield formation. In contrast, the six-row variety Cardinal showed a considerably lower tillering capacity, producing only 524 spikes/m², suggesting a more limited ability to generate additional shoots under the same growing conditions.

These findings highlight the important role of genetic factors in determining spike number, a key component of yield potential in barley. Varieties with high tillering capacity, such as Diana, Ileana, and Gabriela, are likely to be more adaptable to intensive cultivation systems where maximizing the number of productive shoots can significantly enhance overall grain yield. Conversely, varieties with lower tillering, like Cardinal, may require specific management strategies, such as optimized plant density or nutrient supply, to compensate for their reduced spike formation. Overall, this variation underscores the need for genotype-specific management practices to achieve optimal productivity in winter barley cultivation.

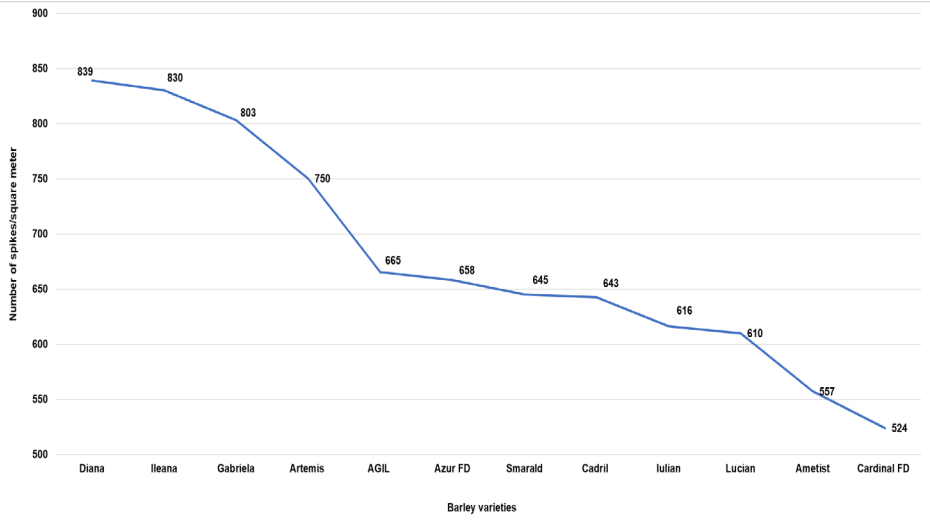

Fig. 4 - Number of spikes per m² in winter barley, average 2023–2025

Based on the data presented in Figure 5, the number of grains per spike exhibited clear variation depending on the barley variety. Among the two-row types, Ileana recorded the highest number of grains per spike, averaging 22.03 grains, whereas in the six-row group, the maximum was observed in Cardinal, with 41.83 grains per spike. This difference reflects the intrinsic genetic distinction between two-row and six-row barley, as six-row varieties typically produce more grains per spike due to their additional fertile florets.

In terms of grain weight per spike, the varieties Cardinal, Cadril, and Agril displayed notably higher values, ranging from 1.73 to 1.87 g (Fig. 5), indicating not only a larger number of grains but also a higher contribution of individual grain weight to overall yield. These results suggest that both spike fertility and grain mass are key determinants of productivity, with six-row varieties potentially offering greater yield potential under optimal conditions.

Understanding these varietal differences is crucial for breeding and cultivation strategies. Varieties with higher grain numbers and spike weight, such as Cardinal, may be prioritized in intensive production systems aimed at maximizing yield, while two-row varieties like Ileana can still provide competitive performance when other agronomic traits, such as disease resistance or grain quality, are considered. Overall, these findings underscore the importance of genotype-specific selection to optimize both yield components and crop performance.

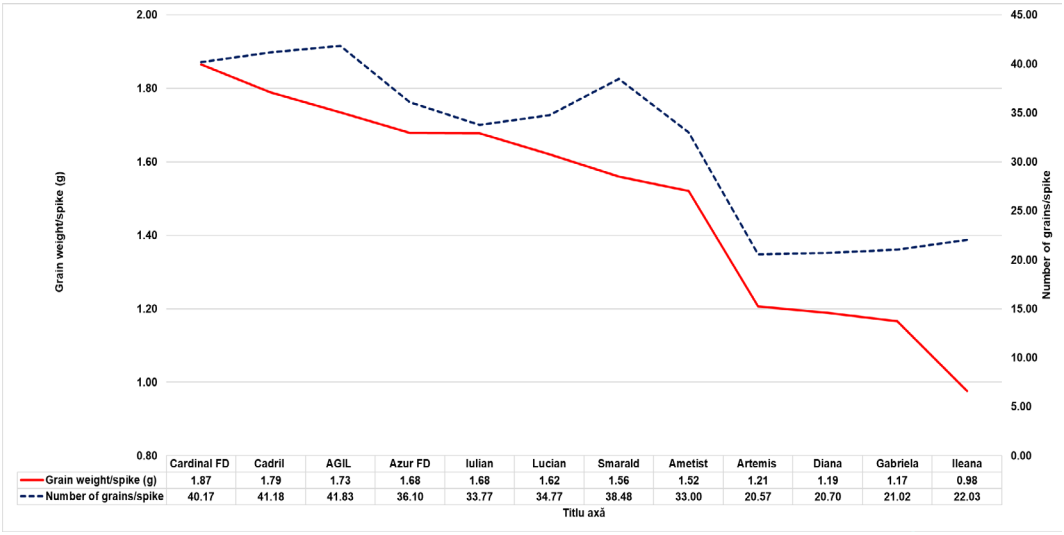

Fig. 5 - Number of grains per spike and grain weight in winter barley, average 2023–2025

The thousand-grain weight (TGW) exhibited noticeable variation among the barley genotypes studied, reflecting differences in grain size and density. Among the two-row varieties, Artemis achieved the highest TGW, reaching 57.7 g, while in the six-row group, Iulian recorded the highest value at 50.3 g (Fig. 6). These results highlight the inherent genetic differences between two-row and six-row barley, as two-row varieties

generally produce fewer but larger and heavier grains, whereas six-row types tend to produce more grains per spike with slightly lower individual grain weight.

This variation in TGW has important implications for yield formation and grain quality. Varieties with higher TGW, such as Artemis and Iulian, contribute not only to total grain yield but also to improved milling and malting characteristics, making them particularly valuable in both food and industrial applications. Selecting genotypes with favorable TGW, in combination with traits like spike number and grains per spike, can therefore enhance overall productivity and optimize the agronomic performance of barley cultivars.

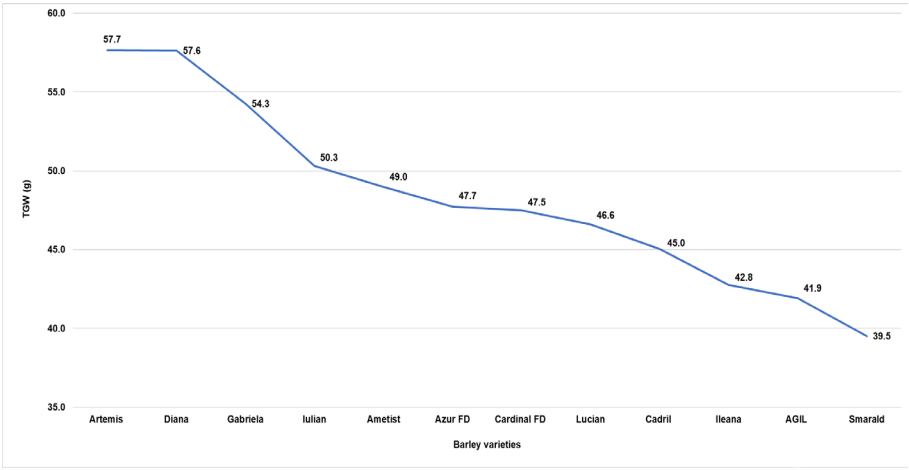

Fig. 6 - Thousand-grain weight in winter barley, average 2023–2025

Analyzing the data presented in Figure 7, it is evident that the barley varieties exhibited distinct responses to the local growing conditions, resulting in a wide range of grain yields. The lowest yield was recorded for Ileana, at 5160 kg/ha, while the highest yield was achieved by Cadril, reaching 8105 kg/ha. The top-performing varieties, with yields ranging from 7483 to 8105 kg/ha, included Cadril, Azur, and Artemis, demonstrating their superior adaptability and productivity under the tested environmental conditions.

These differences in yield reflect the combined effects of genetic potential and environmental interaction, highlighting the importance of selecting varieties well-suited to specific agro-climatic conditions. High-yielding varieties such as Cadril, Azur, and Artemis not only offer greater grain production but also present opportunities for improving resource use efficiency and overall farm profitability. Conversely, varieties with lower yields, like Ileana, may require targeted management interventions or may be better suited to regions with less favorable growing conditions. Overall, these findings underscore the need for genotype-specific recommendations to optimize barley productivity under local conditions.

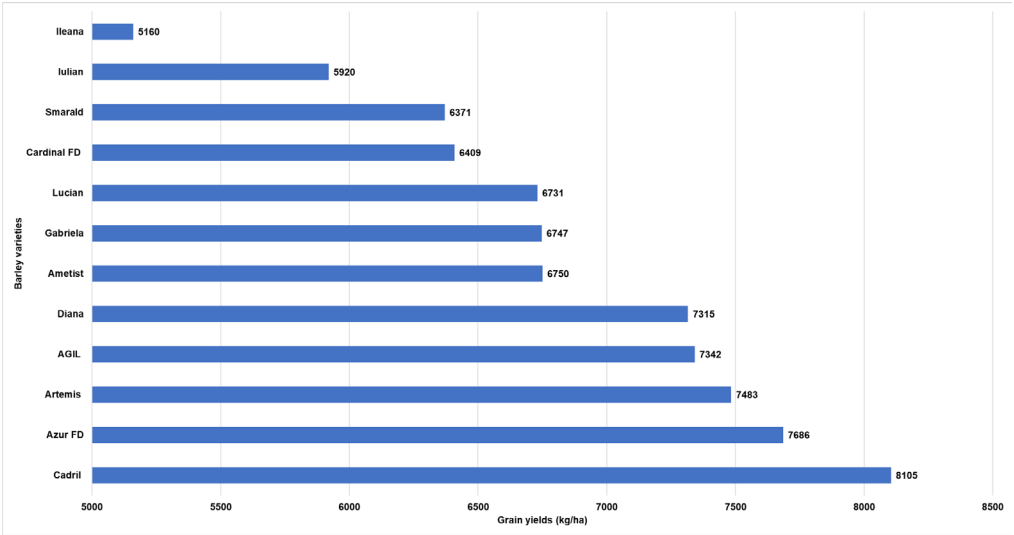

Fig. 7 - Grain yield of winter barley, average 2023–2025

Examination of Table 2 indicates that the varieties Cadril, Azur FD, and Artemis achieved the highest grain yields and production values, making them the most profitable options under the tested conditions. In contrast, varieties with lower yields, such as Ileana and Iulian, were associated with higher production costs per

kilogram of grain and consequently generated lower net profits. These findings emphasize that profitability in barley cultivation is strongly influenced not only by absolute yield but also by the variety's adaptability to local environmental and management conditions. Varieties that combine high yield potential with efficient resource utilization can significantly reduce production costs and maximize revenue, highlighting the critical importance of genotype selection in achieving economic sustainability in barley farming.

Table 2

Economic efficiency of winter barley yield results, 2023 – 2025

No.	Variety	Yield	Production value	Total expenses	Production cost	Gross profit	Net profit
		[kg/ha]	[lei/ha]	[lei/ha]	[lei/kg]	[lei/ha]	[lei/ha]
1	Cardinal FD	6409	5191	2440	0.38	2751	2311
2	Ametist	6750	5467	2440	0.36	3027	2543
3	Smarald	6371	5161	2440	0.38	2721	2285
4	Lucian	6731	5452	2440	0.36	3012	2530
5	Iulian	5920	4795	2440	0.41	2355	1978
6	AGIL	7342	5947	2440	0.33	3507	2946
7	Cadril	8105	6565	2440	0.30	4125	3465
8	Azur FD	7686	6225	2440	0.32	3785	3180
9	Artemis	7483	6062	2440	0.33	3622	3042
10	Gabriela	6747	5465	2440	0.36	3025	2541
11	Diana	7315	5925	2440	0.33	3485	2928
12	Ileana	5160	4180	2440	0.47	1740	1461
The average selling price from ARDS Secuieni: 0.81 lei/kg							

The barley varieties Cadril, Azur, and Artemis stood out as the most profitable, achieving net profits exceeding 3,000 lei/ha (Fig. 8). This economic performance reflects not only their high grain yields but also their efficient use of resources under the prevailing local conditions. These results highlight the importance of selecting varieties that combine strong agronomic performance with favorable economic returns, as profitability in barley cultivation is directly influenced by both yield potential and the variety's adaptability to environmental and management factors.

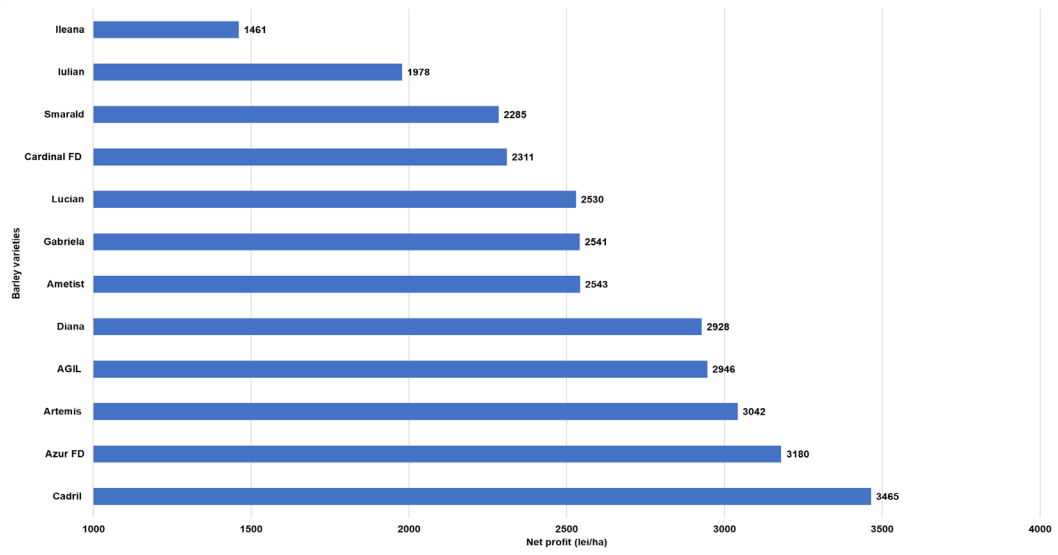

Fig. 8 - Net profit of winter barley varieties, average 2023–2025 (original data)

CONCLUSIONS

Among the 12 winter barley varieties tested in Central Moldova, Cadril, Azur FD, and Artemis achieved the highest grain yields (7,483–8,105 kg/ha), while Ileana and Iulian recorded the lowest yields (5,160–5,920 kg/ha).

The varieties with the highest yields also generated the highest net profits, exceeding 3,000 lei/ha for Cadril, Azur FD, and Artemis. Lower-yielding varieties such as Ileana and Iulian had higher production costs per kilogram and correspondingly lower net profits (1,461–1,978 lei/ha).

Plant height, number of spikes per m², grains per spike, and thousand-grain weight varied by variety, reflecting the impact of genetic characteristics on yield potential and adaptation to local pedoclimatic

conditions. For example, Artemis had the highest thousand-grain weight (57.7 g), contributing to its high economic efficiency.

Varieties that were better adapted to the temperate-continental climate and soil conditions of Central Moldova (Cadril, Azur FD, Artemis) showed both high yield and profitability, highlighting the importance of selecting varieties suited to local pedoclimatic conditions.

The experimental period (2023–2025) was characterized by higher temperatures (+2.2°C) and lower precipitation (-84.4 mm), indicating a drier than normal growing season. Despite these challenges, well-adapted varieties maintained strong performance, emphasizing resilience as a key factor for profitability.

Varieties with lower yields faced higher production costs per kg, demonstrating that economic efficiency is not only a function of yield but also of how well costs are managed relative to production.

Based on the results, the most profitable and recommended winter barley varieties for the region are Cadril, Azur FD, and Artemis, due to their superior yields, high net profits, and adaptability to local pedoclimatic conditions.

ACKNOWLEDGEMENT

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STUDY ON THE PRODUCTIVITY AND ECONOMIC EFFICIENCY OF SPRING WHEAT UNDER THE PEDOCLIMATIC CONDITIONS OF CENTRAL MOLDOVA
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STUDIU PRIVIND PRODUCTIVITATEA ȘI EFICIENȚA ECONOMICĂ A GRÂULUI DE PRIMĂVARĂ ÎN CONDIȚIILE PEDOCLIMATICE ALE CENTRULUI MOLDOVEI

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Keywords: spring wheat, climate-resilient crop, sustainable agriculture, Central Moldova

ABSTRACT

Spring wheat is one of the most important agricultural crops worldwide, playing a crucial role in ensuring global food security. Due to its adaptability to diverse soil and climatic conditions, spring wheat serves as a viable alternative in regions where winter wheat is affected by poor overwintering or exposure to unfavorable environmental factors. The choice of variety is particularly important, as it directly influences yield potential, grain quality, and resistance to both biotic and abiotic stresses. Selecting high-performance varieties adapted to local conditions significantly contributes to achieving stable yields and improving wheat quality, both in terms of technological and nutritional value. From an economic perspective, spring wheat is a competitive crop, allowing farmers to diversify crop rotations, optimize resource use, and take advantage of favorable growing periods. High yields and superior grain quality directly enhance the profitability of agricultural enterprises, making spring wheat a valuable component of modern and sustainable farming systems. In the context of the present study, research conducted at ARDS Secuieni during 2023–2025 evaluated 25 spring wheat genotypes, revealing significant differences in adaptability to local climatic conditions, yield potential, and grain quality. The results highlight the importance of selecting high-performing genotypes adapted to the pedoclimatic characteristics of the region as a key factor for achieving stable and high-quality harvests.

REZUMAT

Grâul de primăvară reprezintă una dintre cele mai importante culturi agricole la nivel mondial, având un rol esențial în asigurarea securității alimentare globale. Datorită adaptabilității sale la diverse condiții de sol și climă, grâul de primăvară constituie o alternativă viabilă în regiunile în care grâul de toamnă este afectat de condițiile slabe de peste iarnă sau de expunerea la factori de mediu nefavorabili. Alegerea soiului este deosebit de importantă, deoarece influențează direct potențialul de producție, calitatea boabelor și rezistența la stresurile biotice și abiotice. Selectarea unor soiuri performante, adaptate condițiilor locale, contribuie semnificativ la obținerea unor recolte stabile și la creșterea calității grâului, atât din punct de vedere tehnologic, cât și nutrițional. Din perspectivă economică, grâul de primăvară este o cultură competitivă, permițând fermierilor diversificarea rotațiilor culturale, optimizarea utilizării resurselor și valorificarea perioadelor favorabile de creștere. Recoltele ridicate și calitatea superioară a boabelor sporesc direct profitabilitatea exploatațiilor agricole, ceea ce face ca grâul de primăvară să fie un component valoros al sistemelor agricole moderne și durabile. În contextul acestui studiu, cercetările efectuate la ARDS Secuieni în perioada 2023–2025 au evaluat 25 de genotipuri de grâu de primăvară, evidențiind diferențe semnificative în ceea ce privește adaptabilitatea la condițiile climatice locale, potențialul de producție și calitatea boabelor. Rezultatele obținute subliniază importanța selecției genotipurilor performante, adaptate la specificul pedoclimatic al regiunii, ca factor cheie pentru obținerea unor recolte stabile și de înaltă calitate.

INTRODUCTION

Climate change poses a major challenge to global agriculture, as rising temperatures, droughts, and weather variability increasingly threaten crop production. Precision agriculture offers solutions to enhance resilience, enabling farmers to optimize irrigation, fertilization, and planting or harvesting timing based on

real-time soil and weather data. By supporting adaptive management and risk reduction, these technologies contribute to more stable and sustainable food production (*Voicea I., 2024*).

The carbon footprint, as an indicator of greenhouse gas emissions from agricultural production, is both a consequence and a driver of climate change. While agricultural activities contribute to global greenhouse gas emissions, the resulting climate impacts in turn affect crop yields, soil moisture, and soil fertility, creating a feedback loop that influences the sustainability and productivity of farming systems (

With climate change increasingly influencing global agricultural systems, spring wheat is becoming one of the most important cereal crops worldwide, playing a key role in ensuring food security. Compared to winter wheat, spring wheat is characterized by a shorter growing cycle, being sown in spring and harvested in late summer or early autumn. This biological characteristic enhances its adaptability to a wide range of climatic and soil conditions and allows farmers greater flexibility in crop management, especially under unpredictable weather patterns (*Li et al., 2025*).

Due to its adaptability, spring wheat can be successfully cultivated in regions where winter wheat is frequently affected by severe winters, insufficient snow cover, or winterkill. As a result, spring wheat contributes to the stabilization of cereal production in areas exposed to climatic risks. In many parts of the world, it is considered a reliable alternative to winter wheat, particularly under conditions of increasing climate variability. However, despite its global importance, the cultivation of spring wheat in Romania remains limited and relatively unexplored, as winter wheat has traditionally dominated cereal production systems. This limited adoption is mainly associated with conventional agronomic practices, the reduced availability of locally adapted varieties, and the lack of comprehensive evaluations regarding its productivity and economic performance under national conditions.

Recent climatic trends, including more frequent drought episodes, temperature extremes, and unstable winter conditions, highlight the potential of spring wheat as a climate-resilient crop. In this context, the selection of suitable varieties is of particular importance, as varietal choice directly influences yield potential, grain quality, and resistance to both biotic and abiotic stresses, such as water deficit and high temperatures (*Mukhtar & Fayyaz-ul-Hassan, 2015*). Furthermore, proper crop management practices, including sowing date, plant density, and fertilization strategies, play a crucial role in optimizing yield formation and grain quality.

From an economic perspective, spring wheat offers significant opportunities for diversifying crop rotations, improving resource-use efficiency, and enhancing farm profitability. Its integration into crop rotations may contribute to better soil management and reduced production risks. Moreover, several studies have demonstrated that sowing management, planting date, and varietal selection have a substantial impact not only on grain yield but also on quality parameters, including protein content and chemical composition, which are essential for both food and feed uses (*Mukhtar & Fayyaz-ul-Hassan, 2015; Slafer & Rawson, 1995*).

Therefore, evaluating the productivity and economic efficiency of spring wheat under specific pedoclimatic conditions, such as those of Central Moldova, is essential for supporting informed agronomic decisions and promoting sustainable and resilient agricultural systems. Overall, spring wheat represents a vital component of modern agriculture, providing production stability alongside significant nutritional and economic value under the challenges posed by climate change.

Climate change, characterized by rising temperatures and precipitation deficits, poses significant challenges for spring wheat cultivation in Central Moldova. Identifying genotypes with high adaptability to these conditions is essential for maintaining both yield and grain quality (*Isticioaia S.F., et al., 2024*).

MATERIALS AND METHODS

The research was conducted at the Agricultural Research and Development Station (ARDS) Secuieni during the 2023–2025 period. The biological material used in the study consisted of 25 Romanian spring wheat genotypes developed at ARDS Turda. The genotype Pădureni, registered in 1973 and considered a reference variety for spring wheat cultivation in Romania, was used as the control (https://scdaturda.ro).

The soil on which the experiments were established was characterized by a moderate nitrogen supply (IN = 2.7), a very high phosphorus content (PAL = 131.3 mg/kg soil; corrected PAL = 106.7 mg/kg soil), and a very good potassium supply (KAL = 208.3 mg/kg soil). The contents of available magnesium (147.2 mg/kg soil) and mobile sulfur (20.5 mg/kg soil) indicated a good nutrient supply. Regarding micronutrients, the soil was well supplied with iron (50.7 mg/kg soil) and copper (3.1 mg/kg soil), while manganese (18.4 mg/kg soil) and zinc (2.5 mg/kg soil) were present at moderate levels. The contents of boron (19.5 µg/kg soil) and

molybdenum (IMo = 6.2) were low. The soil reaction was neutral (pH H_2O = 7.20), and the electrical conductivity of the soil solution (EC H_2O = 144.8 µS/cm) indicated non-saline conditions (Iacobuț D.M, 2025).

The experiment was arranged in the field according to the balanced grid method, with three replications, in order to reduce spatial variability and increase the accuracy of the results. The experimental plot area was 10 m². Sowing was carried out annually between March 7 and 15, at a seeding rate of 600 viable seeds per square meter, using an experimental cereal seed drill with a working width of 1 m, available at the station, with a row spacing of 12.5 cm. Harvesting was performed at the technical maturity of the genotypes using the Wintersteiger experimental combine (Figure 1).

Fig. 1. Experimental plots showing the spring wheat genotypes at ARDS Secuieni

Qualitative analyses were conducted using the NIR 9500 PerkinElmer analyzer at the research unit. For each experimental variant, a 500 g sample was taken. On the NIR analyzer's LED screen, the species *triticale* was selected, and the grain sample was placed into the dedicated sample cup. Within approximately three minutes, the NIR analyzer provided the quality data for the sample (https://www.nitech.ro/ro/produse).

Regarding the climatic conditions during the experimental period, 2023–2025, the growing season of spring wheat was marked by less favorable conditions. During the vegetation period, a significant increase in temperature of approximately 1.5°C was recorded, with March experiencing a pronounced warming of 3.8°C, while May showed a slight cooling (Figure 2).

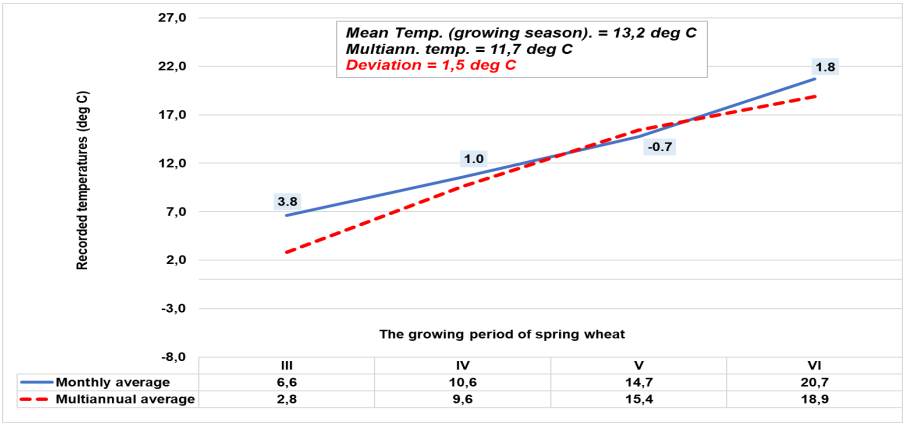

Fig. 2. Temperatures recorded during the growing season of spring wheat in 2023 - 2025 at ARDS Secuieni

In terms of precipitation, throughout the entire vegetation period of spring wheat (from sowing to physiological maturity), deviations from the multiannual mean ranged between -45.6 mm (in June) and +0.6 mm (in March) (Figure 3). Analysis of the annual precipitation totals compared with the long-term average indicated that the studied period was excessively dry, with a total deviation of -58.2 mm (Figure 3).

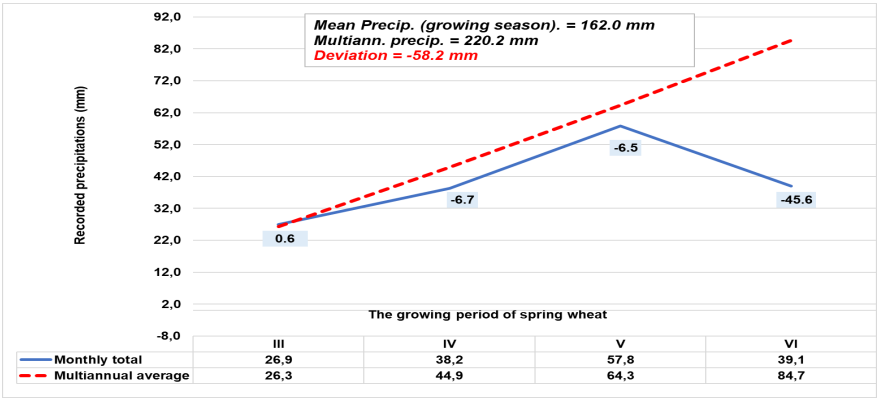

Fig. 3. Precipitation recorded during the growing season of spring wheat in 2023–2025 at ARDS Secuieni

Overall, the climatic conditions during the research period were challenging for spring wheat development, with higher than average temperatures and reduced rainfall, which could have influenced crop growth, phenology, and yield formation.

RESULTS

Grain yields of spring wheat varied considerably depending on genotype, highlighting the essential role of genetic diversity in determining productivity. Under the conditions at ARDS Secuieni, grain yields ranged from 3499 kg/ha for the variant sown with the Pădureni variety to 5788 kg/ha for the variant sown with the experimental line T 2622-22 (Figure 2).

According to the analysis of variance (ANOVA), statistically significant differences were observed among genotypes. Compared to the control variant (Pădureni), all tested variants recorded very highly significant yield increases ($p < 0.001$), as confirmed by the Least Significant Difference (LSD) test, with yield gains ranging from 1142 kg/ha to 2289 kg/ha (Leonte C., Simioniuc V., 2018) (Figure 2).

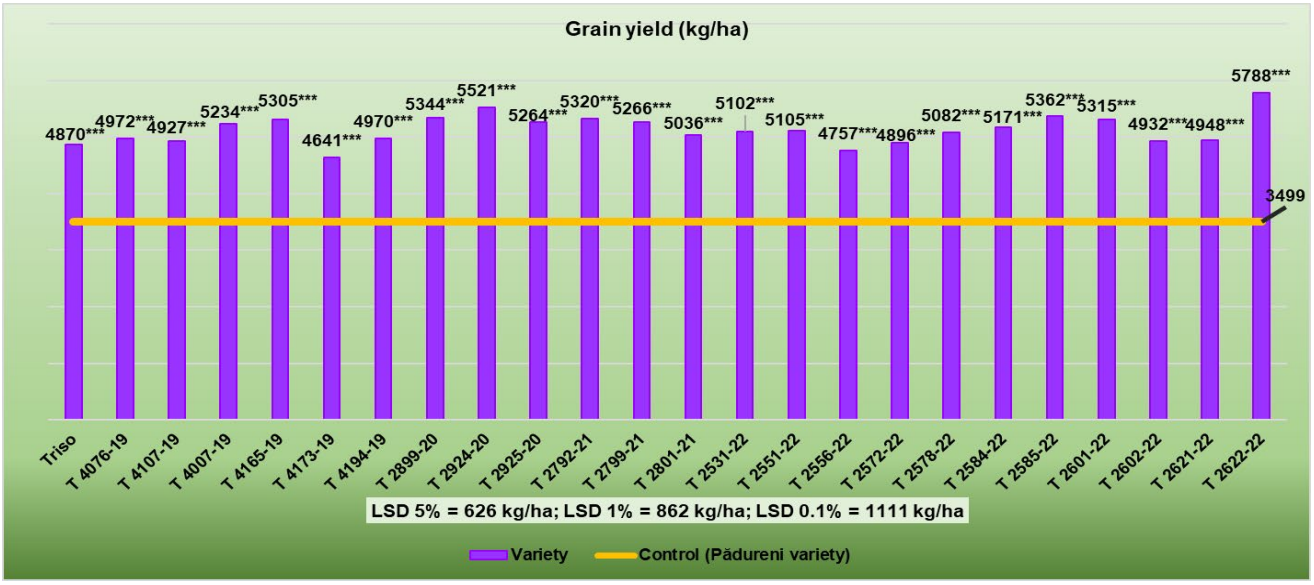

Fig. 2. Grain yields obtained in the comparative trial with spring wheat lines and varieties, ARDS Secuieni (2023 - 2025 Average)

The average analysis of wheat quality traits recorded at ARDS Secuieni during the 2023–2025 period revealed significant variability among varieties with respect to protein content, gluten content, and Zeleny sedimentation index, which are key indicators of baking quality. Protein content ranged from 12.6% to 16%, and gluten content ranged from 25.2% to 33%, with the highest values observed in the Triso and Pădureni varieties, associated with high Zeleny values and superior alveographic W, indicating high baking potential. Starch content was relatively uniform (66–67.8%), while grain hardness and alveographic W exhibited notable differences, with Triso, Pădureni, and T 2572-22 displaying optimal dough elasticity and strength. In contrast, lines T 4165-19 and T 4107-19 showed lower protein, gluten, and W values, indicating reduced baking quality. These results suggest a positive correlation between protein content, gluten strength, and dough resistance, emphasizing the importance of these parameters in the selection of varieties for technological applications (Table 1).

Table 1

Grain quality of yields obtained in the comparative trial with spring wheat lines and varieties, ARDS Secuieni (2023 - 2025 Average)

No.	Variety	Moisture (%)	Protein (%)	Gluten (%)	Zeleny Sedimentation Index (ml)	Starch (%)	Hardness (%)	Alveographic Work (W) (%)
1	Pădureni	11.9	15.4	31.8	71.6	66.1	80.2	335.2
2	Triso	11.9	16.0	33.0	74.5	66.2	79.0	375.9
3	T 4076-19	11.7	15.3	31.4	69.2	66.0	84.9	323.4
4	T 4107-19	11.7	13.6	27.5	55.1	67.7	71.4	282.9
5	T 4007-19	11.6	13.5	27.4	54.9	67.7	75.5	300.4
6	T 4165-19	11.7	12.6	25.2	48.6	67.8	75.4	241.2

No.	Variety	Moisture (%)	Protein (%)	Gluten (%)	Zeleny Sedimentation Index (ml)	Starch (%)	Hardness (%)	Alveographic Work (W) (%)
7	T 4173-19	11.4	14.2	28.8	60.7	66.9	79.4	311.6
8	T 4194-19	11.6	13.7	27.7	56.6	67.0	78.2	257.5
9	T 2899-20	11.5	13.4	27.1	54.2	67.6	71.7	279.4
10	T 2924-20	11.3	13.9	28.4	59.3	67.0	78.2	301.0
11	T 2925-20	11.7	14.3	29.2	62.2	66.8	78.0	312.7
12	T 2792-21	11.7	13.3	26.9	54.6	67.5	68.6	278.8
13	T 2799-21	11.5	14.6	30.0	62.8	66.8	82.7	296.3
14	T 2801-21	11.5	14.7	30.1	64.0	66.7	84.7	314.1
15	T 2531-22	11.6	14.7	30.0	65.6	66.4	77.7	316.3
16	T 2551-22	11.4	14.8	30.3	64.6	66.8	79.1	310.0
17	T 2556-22	11.6	14.8	30.4	65.5	66.5	79.9	318.7
18	T 2572-22	11.6	15.4	31.7	70.0	66.3	79.7	340.4
19	T 2578-22	11.6	15.1	31.1	67.0	66.6	78.5	313.2
20	T 2584-22	11.4	14.8	30.3	64.7	66.7	76.5	290.2
21	T 2585-22	11.4	14.6	29.7	63.1	66.7	79.5	295.4
22	T 2601-22	11.6	13.7	27.8	56.6	67.2	76.1	279.5
23	T 2602-22	11.8	14.0	28.5	58.1	67.4	77.4	303.9
24	T 2621-22	11.7	14.5	29.7	62.8	66.8	80.0	283.3
25	T 2622-22	11.6	14.2	29.0	59.5	67.4	78.0	285.6

From an economic perspective, spring wheat is a productive crop with relatively low cultivation costs. The results obtained during the 2023–2025 period indicate that this crop generates profit even under unfavorable environmental conditions, such as those encountered at ARDS Secuieni. Although the calculation of economic efficiency did not include hectare-based subsidies, Table 2 shows that net profit was positive, with values influenced by the genotype cultivated. Specifically, the plot sown with the Pădureni variety recorded the lowest net profit of 809 RON/ha, while the plot sown with line T 2622-22 achieved the highest net profit of 2,386 RON/ha (Table 2).

Table 2

Economic efficiency of spring wheat yield results, 2023 – 2025

No.	Variety	Yield (kg/ ha)	Production value (lei/ha)	Total expenses (RON/ha)	Production cost (RON/kg)	Gross profit (RON/ha)	Net profit (RON/ha)
1	Pădureni	3499	2869	1906	0.54	963	809
2	Triso	4870	3993	1906	0.39	2087	1753
3	T 4076-19	4972	4077	1906	0.38	2171	1824
4	T 4107-19	4927	4040	1906	0.39	2134	1793
5	T 4007-19	5234	4292	1906	0.36	2386	2004
6	T 4165-19	5305	4350	1906	0.36	2444	2053
7	T 4173-19	4641	3806	1906	0.41	1900	1596
8	T 4194-19	4970	4075	1906	0.38	2169	1822
9	T 2899-20	5344	4382	1906	0.36	2476	2080
10	T 2924-20	5521	4527	1906	0.35	2621	2202
11	T 2925-20	5264	4316	1906	0.36	2410	2025
12	T 2792-21	5320	4362	1906	0.36	2456	2063
13	T 2799-21	5266	4318	1906	0.36	2412	2026
14	T 2801-21	5036	4130	1906	0.38	2224	1868
15	T 2531-22	5102	4184	1906	0.37	2278	1913
16	T 2551-22	5105	4186	1906	0.37	2280	1915
17	T 2556-22	4757	3901	1906	0.40	1995	1676
18	T 2572-22	4896	4015	1906	0.39	2109	1771
19	T 2578-22	5082	4167	1906	0.38	2261	1899
20	T 2584-22	5171	4240	1906	0.37	2334	1961
21	T 2585-22	5362	4397	1906	0.36	2491	2092
22	T 2601-22	5315	4358	1906	0.36	2452	2060
23	T 2602-22	4932	4044	1906	0.39	2138	1796
24	T 2621-22	4948	4057	1906	0.39	2151	1807
25	T 2622-22	5788	4746	1906	0.33	2840	2386
The average selling price from ARDS Secuieni: 0.82 RON/kg							

CONCLUSIONS

Spring wheat productivity at ARDS Secuieni during 2023–2025 varied significantly depending on genotype, highlighting the critical role of genetic diversity. Grain yields ranged from 3499 kg/ha (Pădureni) to 5788 kg/ha (T 2622-22), with all tested genotypes showing statistically significant increases compared to the control.

Wheat quality traits, including protein content, gluten content, and Zeleny sedimentation index, exhibited substantial variability, with Triso, Pădureni, and T 2572-22 displaying superior baking potential due to higher protein, gluten, and alveographic W values.

Economically, spring wheat proved profitable even under suboptimal environmental conditions, with net profit influenced by genotype, ranging from 809 RON/ha (Pădureni) to 2386 RON/ha (T 2622-22).

Overall, a positive correlation between protein content, gluten strength, and dough resistance underscores the importance of these parameters in the selection of varieties for technological and baking applications.

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USING AGRICULTURAL AND FORESTRY RESIDUES IN CONCRETE – A PRACTICAL APPROACH OF TRANSFORMING WASTE INTO VALUABLE RESOURCES
/
UTILIZAREA REZIDUURILOR AGRICOLE ȘI FORESTIERE ÎN BETOANE – O ABORDARE PRACTICĂ DE TRANSFORMARE A DEȘEURILOR ÎN RESURSE VALOROASE

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Keywords: *agro and forestry residues/wastes, construction industry, concrete, waste valorization*

ABSTRACT
Using agro and forestry residues in concrete is a practical approach to sustainable construction, transforming waste into valuable resources while contributing to a circular economy. Making concrete with agro and forestry residues is a method of producing eco–friendly, lightweight concrete by replacing a portion of traditional aggregates (sand, gravel) or cement with processed agricultural and forestry waste. In addition, agro and forestry residues can be directly mixed into the concrete as a partial substitute for cement. These processes helps to reduce environmental impact and valorize waste materials. In fact, using agricultural and forestry residues in concrete is a way to create sustainable and specialized building materials. Forestry and agricultural residues – byproducts of farming and forestry – are increasingly used in the construction industry as sustainable alternatives for traditional building materials, either as aggregates and fillers in lightweight concrete or as supplementary cementitious materials (SCMs). These residues can act as partial substitutes for traditional concrete components like aggregates (sand and gravel) or cement, resulting in new types of concrete, often with reduced weight and different properties. Organic residues can partially or entirely substitute for conventional mineral aggregates to produce materials with reduced density and improved thermal properties. On another hand, SCMs are fine, reactive materials that can replace a portion of the cement, reducing the mix's environmental impact and often improving its long–term performance. This paper explores the sustainable use of agricultural and forestry residues as supplementary materials in concrete production. As global demands for construction materials grow, so does the generation of agricultural and forestry waste, which poses environmental disposal challenges. Incorporating these residues in concrete presents a practical solution for waste valorization, enhancing sustainability in construction by reducing natural resource consumption and mitigating environmental impact.

REZUMAT
Utilizarea reziduurilor agricole și forestiere în beton este o abordare practică a construcției durabile, transformând deșeurile în resurse valoroase, contribuind totodată la o economie circulară. Realizarea betonului cu reziduuri agricole și forestiere este o metodă de producere a betonului ecologic, ușor, prin înlocuirea unei părți din agregatele tradiționale (nisip, pietriș) sau cimentul cu deșeuri agricole și forestiere procesate. În plus, reziduurile agricole și forestiere pot fi amestecate direct în beton ca substitut parțial al cimentului. Aceste procese ajută la reducerea impactului asupra mediului și la valorizarea materialelor reziduale. De fapt, utilizarea reziduurilor agricole și forestiere în beton este o modalitate de a crea materiale de construcție sustenabile și specializate. Reziduurile forestiere și agricole – produse secundare ale agriculturii – sunt tot mai des utilizate în industria construcțiilor ca alternative durabile pentru materialele tradiționale de construcție, fie ca agregate și umpleturi în beton ușor, fie ca materiale cimentare suplimentare (SCM). Aceste reziduuri pot acționa ca înlocuitori parțiali pentru componentele tradiționale din beton, precum agregatele (nisip și pietriș) sau cimentul, rezultând noi tipuri de beton, adesea cu greutate redusă și proprietăți diferite. Reziduurile organice pot înlocui parțial sau total agregatele minerale convenționale pentru a produce materiale cu densitate redusă și proprietăți termice îmbunătățite. Pe de altă parte, SCM–urile sunt materiale fine, reactive, care pot înlocui o parte din ciment, reducând impactul asupra mediului și îmbunătățind adesea performanța pe termen lung. Această lucrare explorează utilizarea durabilă a reziduurilor agricole și forestiere ca materiale suplimentare în producția betonului. Pe măsură ce cererea globală pentru materiale de construcții crește, la fel crește și generarea de deșeuri agricole și forestiere,

ceea ce ridică provocări în eliminarea mediului. Încorporarea acestor reziduuri în beton reprezintă o soluție practică pentru valorizarea deșeurilor, sporind sustenabilitatea în construcții prin reducerea consumului de resurse naturale și atenuarea impactului asupra mediului.

INTRODUCTION

The construction industry is a significant consumer of natural resources, particularly cement and aggregates, whose production involves energy–intensive processes contributing to environmental degradation and carbon emissions. (*Arel, H.Ş. & Aydin, E., 2018; Cheah, C.B. & Ramli, M., 2011*) Agricultural and forestry residues, traditionally considered waste, have emerged as alternative materials with the potential to partially replace cement and aggregates in concrete. Utilizing these materials aligns with circular economy principles and waste hierarchy, providing an eco–friendly approach to waste management while improving certain concrete properties. (*Fadiel, A.& Abu–Lebdeh, T., 2021; Nguyen, H.et al, 2019*)

The construction industry consumes vast quantities of natural resources, with Portland cement production alone accounting for approximately 8% of global anthropogenic CO_2 emissions, exacerbating climate change and resource depletion. Concurrently, agricultural and forestry sectors generate substantial residues—such as rice husk ash (RHA), sugarcane bagasse ash (SCBA), sawdust ash (SDA), wood ash, and raw biomass like sawdust and coconut shells—totaling over 1.5 billion tons annually worldwide, much of which ends up in landfills or open burning, contributing to methane emissions and soil contamination. These lignocellulosic wastes, rich in amorphous silica (40–70%) and pozzolanic compounds, offer untapped potential as supplementary cementitious materials (SCMs) or lightweight aggregates in concrete, enabling partial replacement of cement (5–20%) or sand (10–30%) while aligning with circular economy principles.

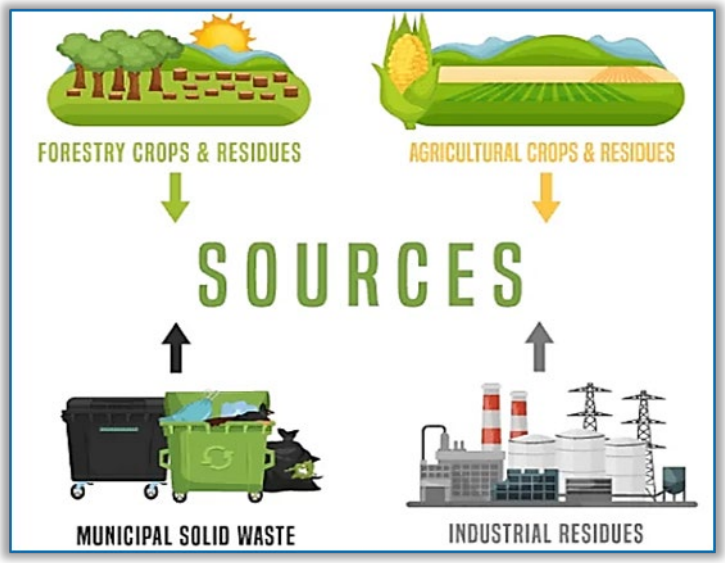

Fig.1. Sources of wastes, in a practical approach to sustainable construction

Many agricultural residues and forestry by–products contain alumino–siliceous compounds, primarily amorphous silica, suitable for pozzolanic activity. The chemical composition and fineness of these ashes enhance their reactivity, improving secondary hydration reactions in concrete matrices. Additionally, these residues have finer particle sizes than cement, which can impact the workability and setting times of concrete mixes. (*Arel, H. Ş.& Aydin, E., 2018; Dias, S et al. 2022; Dias, S et al. 2024*)

AGRICULTURAL and FORESTRY RESIDUES, such as rice husk ash (RHA), sugarcane bagasse ash (SCBA), bamboo leaf ash (BLA), and corncob ash (CCA), serve as sustainable supplementary cementitious materials (SCMs) in concrete production by partially replacing Portland cement up to 10–15%, leveraging their pozzolanic properties from amorphous silica content.(*Harshwardhan, K. & Upadhyay, K.J., 2017; Rabi, J. A.et al, 2009; Mo, K. H.et al, 2020; Raheem, A. A. & Ikotun, B. D., 2020; Thakur, A.et al, 2024*) These materials enhance concrete's mechanical strength, durability, and microstructure through secondary hydration reactions that densify the cement matrix, while reducing cement demand and associated CO2 emissions by 5–17% per cubic meter. (*Maier, D., 2021; Raheem, A. A. & Ikotun, B. D., 2020; Thandavamoorthy, T. S., 2016; Barbuta, M.et al, 2015; Bouabdallah, M. A., 2020*)

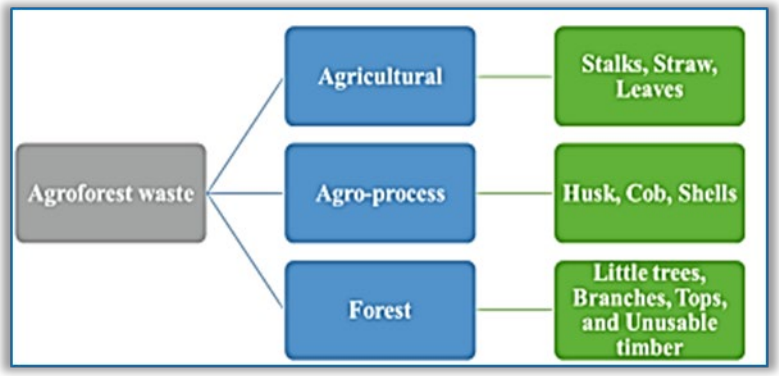

Fig.2. Agro–forest waste

Key residues from agriculture and forestry are primarily lignocellulosic biomass (cellulose, hemicellulose, lignin) from crop parts (stalks, straw, husks, cobs, bagasse) and wood (branches, leaves, bark), along with processing by–products like bran, pulp, and animal by–products. These materials, rich in organic compounds, serve as valuable feedstock. (*Maier, D., 2021; Raheem, A. A. & Ikotun, B. D., 2020; Koopmans, A. & Koppejan, J., 1997*) Key residues and properties of agricultural and forestry residues are:

- RICE HUSK ASH (RHA): High silica content improves compressive and tensile strength; optimal at 10% replacement, reducing workability but boosting long–term durability against sulfate attack.
- SUGARCANE BAGASSE ASH (SCBA): Pozzolanic reactivity enhances strength by up to 13% at 10% substitution; suitable for hot climates, lowers carbon footprint when combusted below 1000°C.
- BAMBOO and CORNCOB ASHES (BLA, CCA): Finer particles than cement increase surface area for better pozzolanic activity; maintain fresh concrete properties with minimal impact on setting time.
- FORESTRY RESIDUES (woody parts, wood ash, sawdust, wood chips and other materials from timber processing): Provide lightweight aggregates or fibers, improving thermal insulation and fire resistance in 3D–printed or ultra–high–performance concretes.

Incorporating these residues refines concrete microstructure via scanning electron microscopy–confirmed gel densification, leading to lower water absorption, higher ultrasonic pulse velocity, and resistance to environmental degradation. These are real performance benefits. In addition, they support circular economy goals by diverting biomass waste from landfills, cutting methane emissions, and enabling CO2 sequestration through carbonation in the matrix. Economic advantages include lower material costs from local sourcing and lifecycle savings in ready–mix production. (Dias, S et al. 2022; Dias, S et al. 2024)

CHALLENGES AND PRACTICAL CONSIDERATIONS

Standardization of ash processing (e.g., controlled combustion) addresses variability in reactivity across climates, ensuring consistent quality. Optimal mix designs limit replacement to 10–20% to avoid workability loss, with pretreatments like grinding enhancing performance. Future scaling requires policy support for waste valorization in construction standards.

Optimal replacement percentages for agricultural and forestry residues in concrete vary by material type, targeting compressive strength (typically M25–M40 grades) and durability metrics like sulfate resistance, permeability, and microstructure densification, with 5–15% cement replacement most common to balance pozzolanic benefits and workability.

Major research gaps and controversies in residue–based concrete (e.g., agricultural/forestry wastes like RHA, SCBA, SDA, wood ash, sawdust) are center on standardization (no unified protocols for processing), long–term performance and durability (limited data on 1+ year exposure to aggressive environments – sulfate, chloride, carbonation, freeze–thaw), variability of sources and scalability (source/wood–type variability affecting reactivity), with fragmented studies often prioritizing compressive strength over holistic assessments. (Dias, S et al. 2022; Dias, S et al. 2024, Rabi, J. A.et al, 2009) Although the technical feasibility is proven, the slow adoption due to conservative standards persist. In addition, the structural use limited despite the non–structural success. Addressing standardized testing and hybrid models could accelerate adoption. Regulatory barriers to high replacement levels (>20–30%) of agricultural/forestry residues (e.g., RHA, SDA, wood ash, sawdust) in concrete stem from conservative building codes prioritizing proven materials, lacking specific provisions for waste–derived SCMs/aggregates, and requiring extensive validation for structural integrity. (Thakur, A. et al, 2024; Siddique, R., 2012; Smith, D., 2017)

PRACTICAL APPLICATION IN CONCRETE

Current practices in utilizing agricultural and forestry residues in concrete have evolved from lab–scale experiments to pilot and commercial applications, particularly in regions with abundant biomass, driven by sustainability mandates and waste management pressures. (Koopmans, A. & Koppejan, J., 1997)

Residues can be utilized as partial replacements for cement or natural aggregates depending on their form and properties. Implementing agricultural waste ashes up to 10–15% replacement levels has been shown to maintain or improve compressive strength, tensile strength, and durability due to the densification of the microstructure. Other raw residues, such as coconut shells or wood chips, can be used as lightweight aggregates, contributing to sustainable lightweight concrete formulations. (Thakur, A. et al, 2024; Siddique, R., 2012; Smith, D., 2017) Furthermore, these materials enhance concrete's thermal insulation and fire resistance properties, adding functional benefits. The main performance targets include:

- Strength: 10% replacement maximizes 28–day compressive strength via silica pozzolanic reactions; beyond 15–20%, early strength drops due to dilution but long–term (90–day) recovers.
- Durability: Peaks at 10% for resistivity (low chloride penetration <1000 coulombs) and sulfate resistance (minimal weight loss <5%); pretreatments like grinding ensure consistency across climates.
- Exceeding 20% risks workability loss (slump reduction 10–20%) and setting delays; use superplasticizers for higher levels in ultra–high–performance mixes.

Optimal replacement percentages for agricultural and forestry residues in concrete target 28–day compressive strength (typically 25–40 MPa for M25–M40 grades) at 10–15% cement substitution, where pozzolanic reactions from silica–rich ashes peak early strength gains of +10–15%; for 90–day strength, the same levels optimize long–term gains (+15–25%) via continued hydration and microstructure densification, as higher replacements (>20%) cause early dilution effects but recover over time.

Recommended mix proportions using sawdust or wood ash as partial replacements in concrete typically involve moderate substitution levels to balance strength and workability:

- SAWDUST ASH (SDA) as cement replacement: Ideal replacement is about 10% by mass of cement. Mix designs often use cement, fine aggregate (or sand), and coarse aggregate (1:2:4), with water–cement ratio around 0.4 to 0.5. At 10% SDA, compressive strength performance is good, maintaining about 80–90% of control strength (0% SDA), while higher substitutions (>15%) tend to cause significant strength reductions.
- WOOD ASH as cement replacement: Partial replacements of 5–15% by weight of cement are common. Wood ash exhibits pozzolanic properties, but compressive strength generally decreases as ash content increases beyond 15%. Studies show that after 90 days, mixes with 5–10% wood ash still reach about 85–90% of the reference mix strength, with performance deteriorating at 20–30% substitution.
- SAWDUST as aggregate replacement: When sawdust is used to replace fine aggregate (sand), modest replacements around 5–10% by volume are recommended to minimize strength loss. Replacement beyond 10% leads to considerable reduction in compressive and tensile strength, although resulting in lighter concrete. Mix proportions vary but a cement:sand:coarse aggregate ratio of 1:2:4 is typical, adjusting volume for sawdust content.

These proportions optimize the practical use of sawdust and wood ash in concrete by achieving a balance between sustainability goals and structural performance for typical construction applications. Practical mix guidance include the following aspects:

- for strength and durability, keep sawdust or wood ash cement replacement ≤10% by weight.
- for aggregate replacement with sawdust, use ≤10% by volume to avoid excessive strength loss.
- maintain water–cement ratio between 0.4–0.5 and consider superplasticizers to retain workability.
- adjust coarse aggregate ratios slightly to compensate for lightweight sawdust.
- cure mixes minimally for 28 days moist curing; extended curing improves pozzolanic reaction benefits.

FORESTRY WASTES, such as wood ash, sawdust, wood shavings, and recycled wood fibers from construction/demolition debris, find practical applications in concrete as supplementary cementitious materials (SCMs), lightweight aggregates, or fibers, typically at 5–20% replacement levels to produce sustainable, low–density mixes with enhanced insulation. (Thakur, A. et al, 2024; Siddique, R., 2012; Smith, D., 2017; Thandavamoorthy, T. S., 2016) Key applications are:

- WOOD ASH as supplementary cementitious materials: Replace 5–10% cement; pozzolanic silica reacts to boost long–term compressive strength (+10–15% at 90 days) and durability via microstructure densification. It is suitable for general–purpose concrete in non–aggressive environments.
- SAWDUST/SHAVINGS as lightweight aggregate: 10–25% volume replacement for sand/gravel; yields lightweight concrete (density 1400–1800 kg/m³) for insulation panels or non–structural elements; improves thermal conductivity (0.5–1.0 W/mK) but requires 1–2% cement increase for strength retention.
- RECYCLED WOOD FIBERS/POWDERS: 5–15% addition in mortars/concretes; enhances tensile/flexural strength and crack resistance in wood–cement composites (WCC); process via shredding to 3–25 mm, mixing with Portland cement in pan mixers for prefabricated boards.
- CONSTRUCTION WOOD WASTE: Up to 20% as filler in permeable / lightweight concretes for pavements, they achieves 10–20 MPa strength with high permeability (4–16 mm/s).

Incorporating these residues transforms environmental liabilities into valuable resources, reducing cement demand through pozzolanic reactions that densify the microstructure and enhance long–term strength. Practical applications include span lightweight insulation panels (density 1400–1800 kg/m³ using sawdust), durable mortars (10% wood/SDA), and permeable pavements (e.g., palm kernel shells achieving 4–16 mm/s permeability at 6–12 MPa). Despite promising results and economic benefits (15–30% cost savings), barriers such as inconsistent reactivity and regulatory gaps persist, underscoring the need for site–specific trials and policy support to scale adoption in sustainable construction, addressing challenges like variability and workability via standardization.

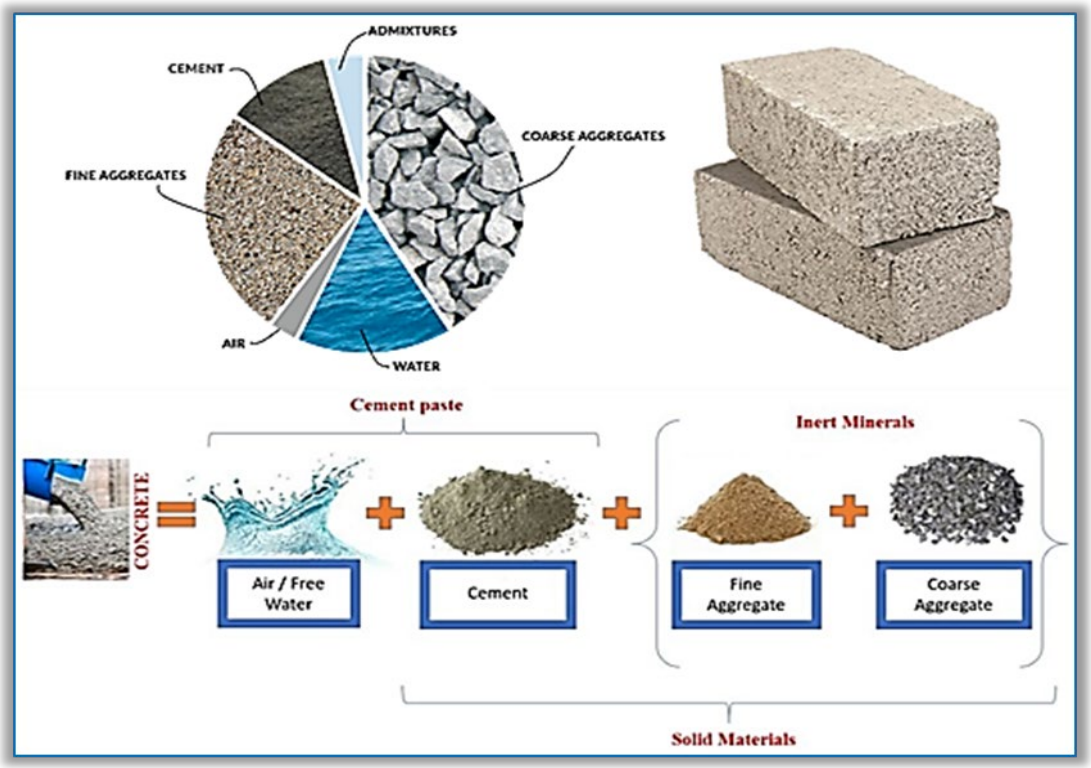

Fig.3. Basic components in concrete

SAWDUST AND WOOD ASH serve as partial replacements in concrete through distinct principles: SAWDUST (2–5 mm particles) acts as lightweight aggregate (10–25% sand replacement by volume), reducing density via high porosity (1400–1800 kg/m³), while WOOD ASH (ground <45 μm) functions as a pozzolanic SCM (5–15% cement replacement by weight), reacting with $Ca(OH)_2$ to form additional CSH gels for strength gains. (Cheah, C. B. & Ramli, M., 2011; Harshwardhan, K. & Upadhyay, K.J., 2017)

- SAWDUST ASH (SDA) as cement replacement: SAWDUST ASH (SDA), produced by controlled incineration of sawdust (<800–1000°C) and sieved to <90–150 μm, acts as a pozzolanic SCM for partial cement replacement (5–15% by weight) due to its high SiO_2 (40–60%), CaO (10–20%), and

amorphous phases that react with cement's $Ca(OH)_2$ to form additional CSH gels, enhancing long–term strength and durability.

- WOOD ASH as cement replacement: WOOD ASH is an effective partial replacement for cement in concrete due to its pozzolanic properties and particulate characteristics. Typically, wood ash can replace cement at 10–20% by weight, providing a balance of strength, durability, and environmental benefits. Wood ash contains high levels of SiO_2, CaO, and Al_2O_3 and has amorphous phases that react with calcium hydroxide released during cement hydration to form additional calcium silicate hydrate (CSH), enhancing concrete strength and durability. It also acts as a filler with spherical particles providing a "ball bearing" effect improving workability.
- SAWDUST as aggregate replacement: SAWDUST serves as a lightweight fine aggregate replacement in concrete (10–25% by volume of sand) to produce low–density mixes (1000–1800 kg/m³) suitable for non–structural elements like insulation panels, blocks, and partitions, leveraging its high porosity for thermal insulation (0.2–0.5 W/mK) while reducing natural sand use. Sawdust's organic cellulose structure creates air voids, lowering density by 20–40% and thermal conductivity, but increases water absorption (20–30%) and reduces compressive strength proportionally to replacement level. It is optimal at 10–25% for M10–M20 grades with moderate durability. Beyond 25%, the strength drops >50%.

WOOD ASH replacement reduces CO_2 emissions by lowering cement demand, diverts biomass waste from landfills, and supports circular economy goals. It shows promise in both conventional and alkali–activated concretes, with ongoing research to optimize durability and mixtures for structural applications. Partial cement replacement is done by dry blending or premixing the ash with cement. Water–to–cement ratio tends to increase slightly with ash content, necessitating superplasticizers for workability. Wood ash improves thermal insulation due to increased porosity and lowers concrete density. (Arel, H. Ş.& Aydin, E., 2018; Dias, S et al. 2022; Dias, S et al. 2024) The main challenges in this replacement are the variability in ash chemistry, depending on wood type and combustion conditions, and the higher water demand, which reduce workability of concrete.

Fig.4. Wood ash

SAWDUST and WOOD SHAVINGS function as lightweight aggregates in concrete by replacing 10–25% of fine aggregate (sand) by volume, yielding low–density mixes (1000–1800 kg/m³) ideal for non–structural insulation panels or blocks. (Cheah, C. B. & Ramli, M., 2011; Harshwardhan, K. & Upadhyay, K.J., 2017; Smith, D., 2017) High porosity improves thermal insulation and sulfate resistance post–28 days; water absorption rises (5–15%) but stabilizes with pretreatments like boiling or alkali soaking. 10–20% replacement with sawdust and wood shavings drops density by 20–40% (e.g., from 2400 to 1400–1600 kg/m³), enhancing load reduction on foundations. In addition, compressive strength falls 20–50% at 15–25% replacement (e.g., 10–20 MPa viable for M10–M20 grades); optimal at 10–15% for 15–25 MPa with minimal tensile loss.

Fig.5. Sawdust, wood shavings and wood powder

WOOD POWDER (finer particles, typically <0.5–2 mm, high surface area) requires greater water and cement adjustments than sawdust (2–5 mm particles) due to its elevated absorption (30–50% vs. 20–30%) and filler effect, acting more like a pozzolanic SCM at 5–15% cement replacement, while sawdust primarily serves as lightweight aggregate at 10–25% sand replacement. (Arel, H. Ş.& Aydin, E., 2018; Dias, S et al. 2022; Dias, S et al. 2024) Moisture content should be controlled to 5–10% (wet basis, oven–dried at 105°C) before mixing to minimize excess water demand (which can exceed 20–30% absorption) and prevent segregation/swelling. The pre–treat is made by air–drying or oven–drying post–sieving.

WOOD ASH, high in SiO2 (20–60%), CaO (10–40%), and Al2O3 (5–15%), serves as a supplementary cementitious material (SCM) in concrete due to its pozzolanic properties from silica, alumina, and calcium oxides, enabling partial cement replacement (5–15% by weight) that reduces CO2 emissions while forming additional calcium silicate hydrate (CSH) gels for long–term strength and durability. Amorphous phases react with cement's calcium hydroxide (CH) for pozzolanic activity, enhanced by grinding to increase fineness and reactivity. Porous particles reduce workability (slump drop 10–20%) but accelerate early hydration, the finer grinding (<45 μm) boosting cumulative heat release and filler effect. Mix designs often use volumetric wood (10–20%), shred/screen to <25 mm and dry (moisture <10%), cement : sand : aggregate ratio 1:2:3, adjusted with 0.4–0.5 W/C, with adding superplasticizers for workability. WOOD ASH 10–15% replacement yields 85–100% of control compressive strength at 28 days, improving to +10–20% at 90 days. Also, wood ash enhances freeze–thaw resistance (e.g., <5% strength loss after 150 cycles) and lowers permeability when blended with fly ash. (*Madurwar, M. V.et al, 2013; Harshwardhan, K. & Upadhyay, K.J., 2017; Siddique, R., 2012; Dias, S et al. 2022; Dias, S et al. 2024*) Challenges include variable moisture/chemicals, and therefore the limitations of wood ash use include variability from wood type/source.

RECYCLED WOOD FIBERS (fiber length commonly 10–30 mm) and POWDERS are increasingly used as concrete reinforcements to enhance toughness, tensile strength, durability, and crack resistance. These fibers, sourced from industrial or postconsumer waste, improve concrete's mechanical properties by bridging micro–cracks and controlling crack propagation, when added at 0.5–2% volume fractions, balancing strength improvements with workability. (Arel, H. Ş.& Aydin, E., 2018; Dias, S et al. 2022; Dias, S et al. 2024) Applications include reinforced concrete slabs, pavements, blocks, composites, and precast elements where tensile/flexural strength is critical. (*Madurwar, M.V.et al, 2013; Smith, D., 2017; Maier, D., 2021*) Recycled wood fibers thus offer a practical and sustainable method to upgrade concrete performance while contributing to circular economy principles by valorizing biomass waste materials. Pre–treatment such as cleaning and sizing improves fiber–matrix bonding.

LONG–TERM DURABILITY AND PERFORMANCE RISKS OF CONCRETE

Assessing long–term durability and performance risks of concrete incorporating agricultural and forestry residues involves a comprehensive approach combining accelerated testing, failure mode analysis, predictive modeling, and field monitoring:

- FAILURE MODE AND RISK ANALYSIS: Identify potential degradation mechanisms (e.g., alkali–silica reaction, sulfate attack, carbonation, and freeze–thaw cycles) relevant to the residue type and exposure conditions. Use checklists and root–cause analyses to focus test protocols on highest–risk factors. Key degradation mechanisms in residue–based concrete (e.g., incorporating RHA, SCBA, SDA, wood ash, sawdust) amplify conventional concrete issues due to residues' high porosity, organics, silica content, and variability, accelerating microcracking, ion ingress, and strength loss.

- ACCELERATED AGING AND DURABILITY TESTS**:** Conduct accelerated life tests simulating environmental stresses (temperature, humidity, chemical exposure) to compress years of aging into months. These tests include rapid chloride permeability, sulfate resistance, freeze–thaw cycling, and alkali–silica reactivity evaluations per ASTM or EN standards.
- MECHANICAL STRESS TESTING: Assess changes over repeated load cycles and mechanical stresses using tensile, compressive, flexural, and fatigue tests to evaluate strength retention and material toughness over time.
- FIELD PERFORMANCE MONITORING: Deploy sensors and periodic inspections to monitor parameters like concrete temperature, moisture content, cracking, and surface degradation under real service conditions. This data validates laboratory predictions and informs maintenance planning.
- MODELING AND PREDICTION: Develop and calibrate degradation models based on test and field data to project service life and performance reliability. Probabilistic approaches accommodate uncertainties and enable adaptive durability management strategies.
- QUALITY CONTROL AND STANDARDS COMPLIANCE: Implement rigorous quality assurance including raw material characterization (e.g., pozzolanic activity, chemical impurities), mix homogeneity, and curing conditions aligned with recognized standards to mitigate variability risks inherent to residues.
- PROCESSING AND SUPPLY CHAINS**:** Residues undergo standardized processing: controlled combustion (600–1000°C for ashes), grinding/sieving (<150 μm), and quality checks.
- OPTIMAL REPLACEMENT LEVELS: Debate on 10–15% vs. 20–30%—early strength dips vs. late gains; some claim >20% viable with additives, others report dilution effects.
- ENVIRONMENTAL CLAIMS: Waste diversion benefits vs. LCA critiques (e.g., transport/processing emissions offsetting CO_2 savings).
- CHALLENGES AND PERSPECTIVES: Variability requires testing, but benefits scale with policy incentives. Hybrid solutions amplify gains for structural use.

Combining these approaches enables informed risk management and ensures that residue–based concrete meets durability requirements, ultimately supporting sustainable structural applications with predictable long–term performance. (Khodaei, H.et al, 2022; Madurwar, M. V.et al, 2013)

CONCLUSION: ENVIRONMENTAL AND ECONOMIC BENEFITS

Agricultural and forestry residues represent promising resources for sustainable concrete production due to their pozzolanic properties and availability. Practical use of these materials can transform waste management challenges into opportunities for eco–friendly construction, promoting circular economy objectives. Future research should focus on optimizing mix designs, exploring treatment methods for raw residues, and scaling up industrial applications for widespread adoption.

The incorporation of agricultural and forestry residues reduces the reliance on conventional raw materials, lowering the carbon footprint of concrete production. It also diverts waste from landfills, lessening environmental pollution. Economically, the use of locally sourced waste materials decreases material costs and supports regional waste management efforts. Overall, this approach supports sustainable construction practices by creating value–added products from otherwise discarded biomass. Agricultural and forestry residues, such as rice husk ash, sugarcane bagasse ash, sawdust ash, wood ash and sawdust represent highly promising resources for sustainable concrete production by serving as supplementary cementitious materials (5–20% cement replacement) or lightweight aggregates (10–30% sand replacement), enhancing strength and durability through pozzolanic reactions.

The technical viability is characterized by the ability of these residues to partially replace conventional cement or aggregates while maintaining or improving long–term mechanical properties and durability. The technical viability of agricultural and forestry residues in concrete is well supported by extensive research demonstrating their effectiveness as supplementary cementitious materials (SCMs) and lightweight aggregates. Rice husk ash (RHA), for example, is a highly reactive pozzolan due to its fine particle size and high amorphous silica content, which significantly enhances the compressive strength and durability of concrete. Studies show that replacing cement with around 10% RHA can increase compressive strength by up to 13–38% at 28 to 90 days, while also improving resistance to sulfate attack, chloride ingress, and carbonation due to the denser microstructure formed by additional calcium silicate hydrate (CSH) gel production.

Similarly, sawdust ash (SDA) exhibit pozzolanic properties that contribute to the hydration process and strengthen concrete matrix, particularly when processed to achieve optimal fineness (<150 μm). Sawdust and wood residues, used as lightweight aggregates, significantly decrease concrete density (to approximately 1400–1800 kg/m³) while improving thermal insulation properties, albeit with some expected strength reduction at higher replacement levels.

Regarding durability performance, residue–based concrete demonstrates improved shrinkage behavior and enhanced resistance to freeze–thaw cycles. However, workability challenges are common due to the high water absorption of organic residues, which can be mitigated by incorporating superplasticizers and adjusting mix water content. Recent advances also highlight the potential of integrating steel fibers with residue–containing concrete to improve tensile strength and ductility. Design mix procedure for lightweight sawdust concrete follows an iterative trial method based on actual standards, adapted for sawdust's high water absorption (20–30%) and low density, targeting M10–M20 grades with 10–25% fine aggregate replacement by volume for non–structural uses like blocks or panels.

Using sawdust ash (SDA), wood ash, and sawdust in concrete as cement replacements (SDA/wood ash at 5–15%) or aggregate replacements (sawdust at 10–25% sand vol.) yields significant environmental and cost benefits by diverting forestry/agricultural waste from landfills, reducing cement/sand demand, and lowering emissions in line with circular economy principles. Challenges include variability (needs standardization) and early workability loss. The high replacements (>20%) suit non–structural uses pending code updates, but future hybrids scale potential is preconized.

Using agricultural and forestry residues in concrete transforms abundant wastes like rice husks, bagasse, sawdust, and wood chips into valuable supplementary cementitious materials or aggregates, delivering multifaceted benefits in sustainability and performance. This practice achieves 20–40% CO_2 emission reductions by curbing cement use, diverts 10–30% of wastes from landfills, and lowers costs by 15–30% via local sourcing, while optimal 10–20% replacements yield 85–115% strength retention, improved durability, and thermal insulation.

— CIRCULAR ECONOMY AND WASTE HIERARCHY INTEGRATION: it excels in the waste hierarchy by prioritizing prevention, reuse, and recovery over disposal, closing sectoral loops between agriculture/forestry and construction to support EU Green Deal targets and valorize nearly 1 billion tons of annual global agro–waste.

— ROLE IN CIRCULAR ECONOMY: Residues close material loops by substituting virgin resources, aligning with EU Green Deal targets for 55% emissions cuts by 2030 and fostering cross–sector synergies between agriculture and construction.

— WASTE HIERARCHY ALIGNMENT: Avoids incineration/landfilling (prevention), repurposes residues as high–value inputs (reuse/recovery), and recovers value from 998 million tons/year global agro–waste, surpassing linear disposal.

— OVERALL IMPORTANCE**:** Amid surging concrete demand exceeding 4 billion tons yearly, this scalable approach enhances resource efficiency, economic resilience—especially in agro–rich areas and drives innovation for construction sector and concrete manufacturing.

Vital for sustainability amid rising concrete demand (4+ billion tons/year), it addresses agro–forestry surpluses, standardizes, and scales for rural infrastructure, though pre–processing uniformity remains key. Using agricultural and forestry residues in concrete represents a transformative practice that converts abundant wastes like rice husks, bagasse, sawdust, and wood chips into high–value construction materials, aligning seamlessly with circular economy principles and the waste hierarchy. Using agricultural and forestry residues in concrete transforms abundant wastes like sawdust and wood chips into valuable supplementary cementitious materials (SCMs) or aggregates, reducing environmental impacts while enhancing material performance. This practice supports the circular economy by prioritizing waste hierarchy principles—preventing disposal through reuse and recycling. Transforming waste into valuable resources embodies the core principle of the circular economy, shifting from linear "take–make–dispose" models to regenerative systems that eliminate waste through design–driven reuse, recycling, and regeneration. This approach maximizes resource value by converting byproducts—like agricultural and forestry residues—into inputs for new processes, prioritizing prevention over disposal.

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CHROME PLATING FOR IMPROVE PERFORMANCE OF AGRICULTURAL EQUIPMENTS UNDER DEMANDING CONDITIONS FOUND IN FARMING OPERATIONS
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PLACAREA CU CROM PENTRU ÎMBUNĂTĂȚIREA PERFORMANȚEI UTILAJELOR AGRICOLE ÎN CONDIȚIILE SOLICITANTE ÎNTÂLNITE ÎN EXPLOATĂRILE AGRICOLE

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ABSTRACT
Common agricultural parts that often fail without protective coatings include components exposed to intense mechanical wear, moisture, chemicals, and soil abrasion. These parts are vulnerable to corrosion, pitting, cracking, and structural weakening, leading to premature failure and costly downtime. Without coatings like hard chrome plating, powder coatings, thermal spray coatings, or nickel plating, these parts degrade quickly through rust, cracks, and surface damage, compromising equipment safety, reliability, and productivity. Protective coatings form a barrier against moisture, chemicals, UV light, and physical wear, extending the service life of critical agricultural components and reducing maintenance costs. These coatings act as physical and chemical barriers, extending the service life of parts such as fasteners, harvester rolls, joints, and frames that encounter manure and fertilizer exposure, ultimately reducing maintenance and replacement frequency. Chrome plating in agriculture ensures parts withstand intense mechanical contact and corrosive environments, extending operational life and enhancing productivity. Agricultural equipment manufacturers frequently choose premium industrial hard chrome finishes to improve performance under the demanding conditions found in farming operations.

REZUMAT
Piesele agricole comune care adesea cedează fără straturi de protecție includ componente expuse la uzură mecanică intensă, umiditate, substanțe chimice și abraziune a solului. Aceste piese sunt vulnerabile la coroziune, găurire, crăpături și slăbire structurală, ceea ce duce la defectări premature și perioade de oprire costisitoare. Fără straturi precum placarea cromată dură, straturile cu pulbere, straturile cu pulverizare termică sau placarea cu nichel, aceste piese se degradează rapid prin rugină, crăpături și deteriorare la suprafață, compromițând siguranța, fiabilitatea și productivitatea echipamentelor. Straturile de protecție formează o barieră împotriva umidității, substanțelor chimice, luminii UV și uzurii fizice, prelungind durata de viață a componentelor agricole critice și reducând costurile de întreținere. Aceste straturi acționează ca bariere fizice și chimice, prelungind durata de viață a pieselor precum elementele de prindere, rolele de recoltare, îmbinările și cadrele care sunt expuse la gunoi de grajd și îngrășăminte, reducând în cele din urmă frecvența întreținerii și înlocuirilor. Placarea cromată în agricultură asigură că piesele rezistă unui contact mecanic intens și mediilor corozive, prelungind durata de viață operațională și sporind productivitatea. Producătorii de echipamente agricole aleg frecvent finisaje industriale premium din crom dur pentru a îmbunătăți performanța în condițiile solicitante întâlnite în exploatările agricole.

INTRODUCTION

Farming operations require high–performance equipment with plated parts to endure abrasion from soil and crops, corrosion from moisture and chemicals, and friction during extended use, minimizing downtime during critical seasons like planting and harvest. Large–scale mechanized farming demands reliable tractors, combines, and harvesters that operate continuously over vast fields amid labor shortages and climate variability. (Malvajerdi, A. S., 2023; Mohapatra, G. & Sahay, S. S., 2017; Ertani, A.et al, 2017) Common agricultural parts that often fail without protective coatings include components exposed to intense mechanical wear, moisture, chemicals, and soil abrasion. These parts are vulnerable to corrosion, pitting, cracking, and structural weakening, leading to premature failure and costly downtime. Chrome plating is a highly effective and widely used solution for protecting and improving the performance of vulnerable agricultural parts. (Sun, J.et al, 2022; Ertani, A.et al, 2017; Romankiw, L. T. & O'Sullivan, E. J., 1997)

Plated components like hydraulic rods and blades must resist seizing, wear, and rust to support precision agriculture with GPS and sensors, cutting manual effort by 50–70%. These parts extend service life 2–10 times, reducing repair frequency and lubricant needs while boosting yield optimization. Blades, hydraulic rods, and cutting edges rank among the agricultural parts most needing plating due to constant exposure to abrasion from soil, crops and chaff. Plating reduces wear, heat, and lubricant needs while boosting corrosion resistance in damp fields.

Modern farming operations demand high–performance equipment to handle large–scale soil preparation, precision planting, efficient harvesting, and resource optimization amid labor shortages, climate variability, and rising yields needs. High–performance gear cuts manual effort by 50–70%, integrates IoT/drones for data–driven decisions on irrigation and nutrients, and withstands abrasion/moisture via durable coatings on blades/plows. This sustains productivity, lowers costs, and supports sustainable practices like precision agriculture. Key equipment needs are:

- tractors and autonomous systems: GPS–enabled, AI–integrated models for accurate navigation, reduced labor, and real–time soil monitoring in tillage and transport.
- planting/seeding machines: Precision drills with variable rate tech and sensors for uniform seed placement, boosting germination by 20–30% on expansive fields.
- harvesting combines: Multi–function units with auto–steer and crop sensors for faster, low–waste operations during short harvest windows.

Modern farming operations demand high–performance equipment with plated parts – blades and cutting edges, hydraulic rods and moving parts, fasteners and frames – to ensure reliability, minimize downtime, and withstand abrasion, corrosion, and friction from soil, crops, chemicals, and extended field use. Fasteners, brackets, and frames require zinc or phosphate coatings as sacrificial layers against rust from wet soil and pesticides, ensuring structural integrity in combines and irrigation systems. These platings cut maintenance by 30–50% and support sustainable operations with fewer replacements. Blades, cutting edges, and hydraulic rods/cylinders represent the agricultural parts most needing chrome plating due to their exposure to intense abrasion from soil, crops, and chaff, plus friction and mechanical stress.

Fig. 1 – Plated components in farming operations

METALLIC PLATING is the process of depositing a thin layer of metal onto the surface of a substrate, such as another metal or plastic, to enhance its properties. Metallic plating serves functional roles like improving corrosion resistance, wear resistance, electrical conductivity, and paint adhesion on base materials. It also enables cost–effective designs by allowing cheaper substrates, such as carbon steel, to gain protective qualities from coatings like chromium or nickel. This technique boosts product durability and performance across industries, from automotive and electronics to medical devices and fasteners. Additionally, it provides aesthetic enhancements, such as shiny finishes, while reducing friction and increasing magnetism where needed.(Rodríguez, R.et al, 2018) There are many different types of metal

plating and in its simplest definition, metal plating is a thin covering of metal on top of another metal. This type of metal plating has been used for hundreds of years and is a critical part of modern technology.

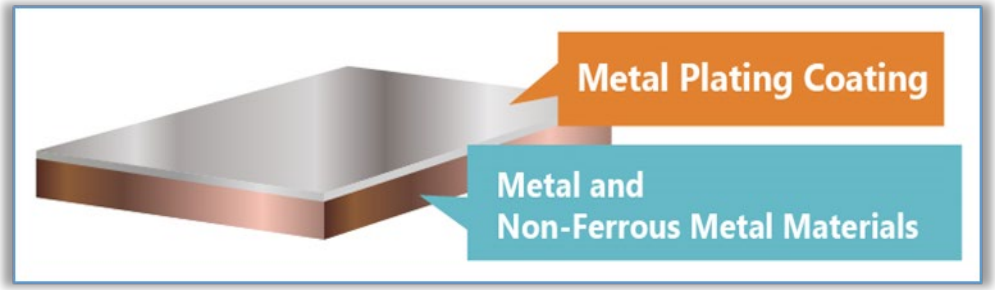

Fig. 2 – Metallic plating

METALLIC PLATING serves key functional roles in agricultural equipment parts by enhancing corrosion resistance, wear protection, lubricity, and durability against harsh environmental factors like soil moisture, fertilizers, pesticides, and mechanical stress. The main key aspects are:

- corrosion protection: Zinc and cadmium platings act sacrificially on steel fasteners and frames, preventing rust in wet, acidic field conditions and extending part life without base material degradation.
- wear and friction reduction: Hard chrome and electroless nickel coatings on blades, plows, and moving components increase surface hardness (up to 70 HRC) and lower friction, minimizing abrasion from soil/ crop contact and reducing lubricant needs.
- operational enhancements: Copper underlayers improve heat dissipation in engine parts, while phosphate coatings retain oils for smoother bearing operation, overall boosting equipment reliability and cutting maintenance downtime.

METALLIC PLATING is crucial for agricultural equipment parts, significantly extending service life, reducing maintenance costs, and ensuring reliable performance in harsh conditions like moisture, chemicals, abrasion, and temperature extremes.

- durability and lifespan extension: Plating with zinc, nickel, or chrome creates protective barriers that prevent corrosion from damp soil, fertilizers, and pesticides, while boosting hardness (e.g., chrome up to 70 HRC) to resist wear on blades, plows, and fasteners. This minimizes breakdowns, cuts downtime during critical farming seasons, and lowers replacement needs, directly supporting operational efficiency.
- cost and performance savings: Hard chrome and electroless nickel reduce friction and seizing in moving parts, decreasing lubricant use and repair frequency, which saves money over time compared to uncoated or low–grade materials. Enhanced heat dissipation from copper underlayers prevents overheating during long field hours, further prolonging equipment usability.
- industry–wide impact: These coatings enable customized, high–quality machinery that withstands UV, wind, and mechanical stress, fostering sustainable farming by reducing waste and environmental impact from frequent part replacements.

There are several plating methods and many variations. In one method, a solid surface is covered with a metal sheet, and then heat and pressure are applied to fuse them. Other plating techniques include electroplating, vapor deposition under vacuum, and sputter deposition. (Ertani, A.et al, 2017; Fister, D., 2010; Snyder, D. L., 2000; Wang, L. K., & Wang, M.H.S., 2025, (Rodríguez, R.et al, 2018)) Recently, plating often refers to using liquids. Metallizing refers to coating metal on non–metallic objects.

Common platings include zinc (corrosion), nickel (hard, corrosion), copper (conductivity, base), silver (conductivity, decorative), and gold (decorative, corrosion), differing by color, feel, and magnetic response. The main metals used for plating are gold, silver, nickel, copper, chromium, and zinc, selected for their unique properties like conductivity, corrosion resistance, and durability. (Astanin, V. K. et al, 2018; Vinokurov, E. G.et al, 2016; Ertani, A.et al, 2017) Rhodium provides superior wear/corrosion resistance and shine for jewelry and electronics. Cadmium acts as a sacrificial layer in aerospace/marine uses, while platinum and palladium offer inertness for medical/dental applications.

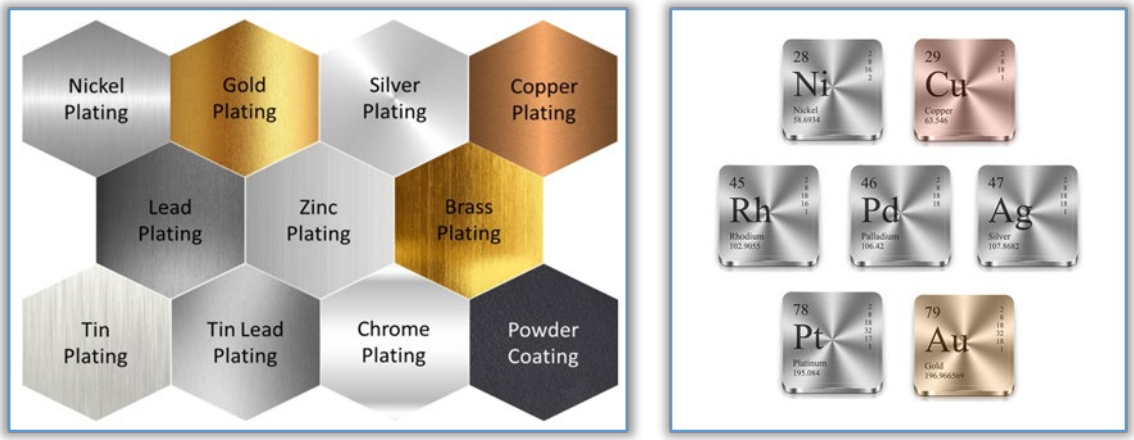

Fig. 3 – Common platings

CHROME PLATING excels in agricultural equipment by providing superior wear resistance and corrosion protection against soil abrasion, fertilizers, and chemicals, significantly extending component life and reducing downtime. HARD CHROME PLATING is widely applied to agricultural equipment parts like blades, plows, hydraulic rods, and thrashing components to boost hardness, reduce friction and combat wear from abrasive crops, soil, and chaff. Hard chrome plating is widely used on crop–handling tools, moving parts, and fasteners to cut repair costs, it maximize uptime during harvest seasons, and lower lifecycle expenses through re–plating options. Blades maintain sharpness longer, with chrome enabling re–plating after wear to restore dimensions and performance. This is vital for agricultural or industrial cutters exposed to sticky, corrosive, or high–abrasion materials, cutting downtime and replacement costs. Chrome plating extends the service life of cutting blades by providing a hard, low–friction surface that resists abrasion, corrosion, and material adhesion, reducing wear from repeated cutting cycles. Chrome plating acts as a sacrificial barrier against moisture, chemicals, and oxidation, minimizing pitting and edge erosion.

MATERIALS AND METHODS

Plating usually refers to coating a thin layer of metal over the other material surface that can be metal or non–metal. Metallic plating primarily uses base metals for corrosion resistance and wear protection, and precious metals for conductivity and aesthetics. The main metals used for plating agricultural equipment parts are zinc, nickel (often as zinc–nickel alloy or electroless nickel), chrome, copper, and cadmium, chosen for corrosion protection, wear resistance, and durability in harsh field conditions like moisture, chemicals, and abrasion. (Ertani, A.et al, 2017; Fister, D., 2010; Snyder, D. L., 2000; Wang, L. K., & Wang, M.H.S., 2025) These platings extend equipment lifespan by countering rust, friction, and temperature swings in farming operations.

The various plating process types are methods used to apply a thin layer of metal onto a substrate (base material) to enhance its properties, such as corrosion resistance, wear resistance, hardness, or aesthetics. These methods are broadly classified based on the mechanism used to deposit the metal. The two fundamental types of metal plating processes are ELECTROPLATING and ELECTROLESS PLATING.

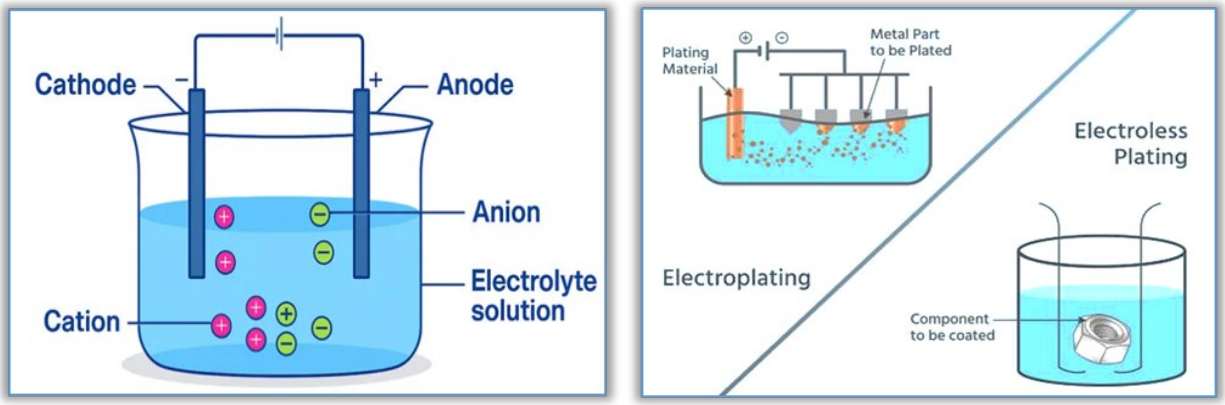

Fig. 4 – Various plating process types

Other significant industrial methods include IMMERSION PLATING and THERMAL SPRAYING. Main types of metal plating differ primarily in their deposition mechanisms.

- ELECTROPLATING uses an electric current passed through an electrolyte solution to deposit metal ions from an anode onto a conductive cathode substrate, enabling precise thickness control and uniform coatings on simple geometries. It suits applications needing high durability, like automotive parts, but requires electrical equipment and works best on conductive surfaces.
- ELECTROLESS PLATING relies on a chemical reduction reaction without external electricity, achieving uniform coverage on complex or non–conductive shapes via autocatalytic deposition. This method excels in corrosion resistance for intricate parts in electronics or aerospace, though it demands precise chemical baths.
- IMMERSION PLATING deposits metal through a displacement reaction by immersing the substrate in a solution of more noble metal ions, forming thin, self–limiting layers without power. It provides simple corrosion protection but yields thinner coatings than electroplating, ideal for basic applications on active metals.
- THERMAL SPRAYING, in which heat feedstock (powder/wire) to molten state using plasma, HVOF (high–velocity oxy–fuel), or flame spray, then accelerate particles at supersonic speeds (up to 1000 m/s) to impact and flatten on the prepared surface, creating a layered coating via mechanical interlocking (no diffusion).

Plating methods fall into electrolytic (current–driven, such Hard Chrome Plating, Nickel Electroplating or Zinc Electroplating) and electroless (chemical/autocatalytic, such Electroless Nickel or rarely, Electroless Copper) categories, with thermal sprays for heavy–duty applications. Nickel and chrome dominate due to resistance against abrasive soils, ammonium nitrate corrosion (1,250 μm/year), and mechanical stress. Electroless methods suit irregular parts like sprayer nozzles, while HVOF (with WC–Co, CrC–NiCr) handles high–impact tillage. Trivalent chrome transitions address REACH/RoHS regulations.

SWOT ANALYSIS: CHROME PLATING FOR AGRICULTURAL EQUIPMENT PARTS

Chrome plating plays a critical role in agricultural equipment by providing exceptional hardness, low friction, and corrosion resistance, extending part life on blades and hydraulics to minimize downtime and support large–scale mechanized farming. Conduct a SWOT analysis by gathering diverse input on internal strengths/weaknesses and external opportunities/threats, then prioritizing and strategizing to inform decisions like those for chrome plating in agriculture.

SWOT stands for Strengths, Weaknesses, Opportunities, and Threats, serving as a simple matrix tool to assess these four key factors. It systematically identifies internal capabilities (strengths and weaknesses) and external influences (opportunities and threats) to inform decision–making. Decision–makers use it to challenge assumptions, prioritize initiatives, and develop strategies like matching strengths to opportunities (SO) or minimizing weaknesses against threats (WT).

Fig. 5 – Concept of SWOT Analysis

Strengths

- Chrome plating provides substantial technical advantages that make it a preferred choice for agricultural equipment manufacturers. The most significant strength is its exceptional wear and corrosion resistance, which dramatically extends the lifespan of equipment components exposed to intense mechanical contact, abrasive materials, and harsh chemical environments. Hard chrome plating increases surface hardness to approximately 68–70 Rockwell C, offering superior protection against the cutting, thrashing, and friction inherent in crop harvesting operations.

— The economic benefits are compelling for equipment owners. Chrome–plated components significantly reduce maintenance costs and equipment downtime by extending service life and preventing corrosion–related failures. In agricultural operations where fertilizers such as ammonium nitrate create corrosion rates of 1,250 micrometers annually on unprotected steel, chrome plating's protective barrier becomes essential. The lubricious surface properties reduce friction between moving parts, improving mechanical efficiency and reducing energy consumption during equipment operation.

— From a manufacturing perspective, chrome plating demonstrates adaptability to complex geometries. The electrochemical process allows uniform coating deposition on irregular shapes, holes, and crevices at precisely controlled thicknesses (2–250 micrometers), making it suitable for diverse agricultural component designs. Additionally, the process has established credibility with over 80 years of industrial implementation, providing manufacturers and farmers confidence in reliability.

Weaknesses

— Despite technical advantages, chrome plating faces significant internal limitations. The prohibitive cost structure represents the foremost weakness, requiring specialized equipment, high–quality materials, and skilled labor. Initial plating investments exceed alternative coating methods, and while long–term ROI improves, smaller agricultural equipment manufacturers may lack capital for adoption. Long–term ROI in plating comes from enhanced part durability, reduced replacement costs, improved performance (strength, corrosion resistance), and operational savings, especially with advanced techniques like brush plating that repair rather than replace components, saving on new part procurement, downtime, and waste, driving significant value beyond initial investment.

— Environmental and health hazards associated with traditional hexavalent chromium plating constitute a critical weakness. Hexavalent chromium (Cr(VI)) is a recognized carcinogen, requiring strict hazard controls and worker protection protocols. The process generates toxic hexavalent chromium waste, hazardous fumes, and creates significant wastewater treatment challenges, increasing operational complexity and regulatory compliance costs. Hexavalent chromium poses toxicity risks, strict regulations, and waste disposal challenges, limiting scalability for agricultural applications.

— Higher material and energy demands for thick hard chrome layers increase upfront expenses compared to zinc or nickel alternatives, while requiring specialized facilities and skilled labor. Defects such as burned deposits, mud cracking, or roughness from poor base preparation compromise performance on blades and plows, necessitating rework.

— The process complexity demands meticulous technical control. The electroplating procedure requires precise management of current density, temperature, plating time, and bath composition to achieve acceptable coating quality. Process interruptions without current controls can compromise finish quality in conventional hard chrome processes, leading to rework and additional costs. Additionally, the energy intensity of electroplating consumes substantial electricity, increasing operational costs and carbon footprint compared to emerging alternatives.

Opportunities

— The global chrome plating market presents substantial growth opportunities. This growth trajectory reflects mounting agricultural equipment demand in emerging markets, experiencing rapid industrialization.

— Technological innovation offers significant opportunities through adoption of trivalent chromium (Cr(III)) plating, which reduces toxicity while maintaining performance comparable to hexavalent chromium. Trivalent chromium processes require lower current densities, consume less energy, generate approximately 30 times less hazardous sludge, and improve throwing power, enabling increased rack densities and reduced production costs. This technology facilitates environmental compliance while improving operational economics.

— Thin Dense Chrome (TDC) technology represents another growth avenue, producing extremely hard coatings (70 Rockwell C) with minimal thickness (0.00005–0.0002 inches), lower energy consumption, and reduced environmental impact compared to conventional hard chrome. Additionally, composite coating strategies combining chrome with ceramic coatings or electroless nickel present opportunities for enhanced durability in agriculture's increasingly harsh chemical environments.

- The circular economy framework creates opportunities for chrome plating to serve as a cost–effective life–extension strategy. By extending equipment service life by 40–100%, chrome plating reduces the demand for new manufacturing and resource consumption, aligning with sustainability objectives while generating profitable plating services.

Threats

- Regulatory pressures constitute the most formidable external threat. The European Union's REACH (Registration, Evaluation, Authorization, and Restriction of Chemicals) regulation and RoHS (Restriction of Hazardous Substances) directive severely restrict hexavalent chromium usage. The US Environmental Protection Agency (EPA) and Occupational Safety and Health Administration (OSHA) have established stringent occupational exposure limits (5 micrograms per cubic meter), creating compliance costs that can be prohibitively expensive for smaller operations.
- Alternative coating technologies pose competitive threats to market dominance. High Velocity Oxy–Fuel (HVOF) thermal spray coatings offer superior wear resistance in specific applications, while electroless nickel plating provides excellent corrosion protection with improved deposit uniformity. Ceramic coatings for agricultural machinery demonstrate high temperature resistance, durability spanning 2–5 years, and versatility across diverse substrates. These alternatives collectively capture market share, particularly among environmentally conscious manufacturers.
- Agricultural chemical exposure creates persistent threats to coating effectiveness. Fertilizers, particularly ammonium nitrate, potassium chloride, and urea–ammonium–nitrate (UAN) solutions, accelerate corrosion rates on traditional protective coatings, with galvanized components experiencing zinc loss of 250–280 micrometers annually. While chrome plating mitigates these effects, the harsh chemical environments demand increasingly sophisticated coating specifications, increasing costs.
- Supply chain volatility and material cost fluctuations in chromium availability can disrupt production schedules and inflate operational expenses. Furthermore, the high learning curve for trivalent chromium adoption creates temporary productivity losses and technical challenges for facilities transitioning from hexavalent processes, requiring worker retraining and equipment modifications.

STRATEGIC PERSPECTIVES & MARKET TRENDS

Chrome plating excels in agricultural equipment by providing superior wear resistance and corrosion protection against soil abrasion, fertilizers, and chemicals, significantly extending component life and reducing downtime. (Rodríguez, R.et al, 2018, Astanin, V. K. et al, 2018; Sun, J.et al, 2022) The strategic perspectives can be summarized as follow:

- For equipment manufacturers: Chrome plating remains strategically valuable where long–term equipment reliability justifies initial investment, particularly for premium agricultural machinery targeted at commercial operations. The technology excels for high–wear components including bailing hooks, harvester rolls, stripper plates, and hydraulic cylinders. Manufacturers should prioritize trivalent chromium adoption to navigate regulatory landscapes while maintaining performance characteristics.
- For agricultural operators: The extended equipment lifespan and reduced downtime justify chrome–plating investment despite higher component costs. In regions with challenging soil chemistry or extreme humidity (coastal areas with 80%+ relative humidity), chrome plating provides exceptional value through corrosion prevention.
- For plating service providers: The market inflection toward sustainable alternatives creates competitive pressures requiring technology diversification. Providers must invest in trivalent chromium capabilities, thin dense chrome systems, and complementary coating technologies (electroless nickel, ceramic) to capture emerging demand segments while maintaining regulatory compliance.
- For regulatory and policy perspectives: The transition toward less–toxic plating chemistries aligns with global environmental protection objectives while supporting industrial competitiveness through technological innovation pathways.

Strategic perspectives on chrome plating for agricultural equipment emphasize leveraging its superior durability for competitive advantage while navigating regulatory pressures through innovation and sustainable practices. (Basavaraja, R. J. et al, 2023; Vinokurov, E. G.et al, 2016)

Market trends affecting chrome–plating demand in agriculture include regulatory shifts away from hexavalent chromium, growth in mechanized farming equipment, and rising adoption of eco–friendly alternatives, balancing sustained need for durability with compliance pressures.

- Driving trends include the expanding global agriculture machinery sector boosts demand for chrome–plated bars in hydraulics, pistons, and blades, with the chrome plated bar market projected to grow, driven by wear–resistant needs in harsh field conditions.
- Restraining trends include environmental regulations, alternatives and costs. Shift to electroless nickel or composites, plus raw material price volatility, hampers traditional chrome use. Higher costs and retooling delay equipment upgrades, but compliant platings maintain durability; overall, regulations spur innovation, reducing environmental risks while sustaining demand via substitutes. EU REACH and RoHS regulations severely restrict hexavalent chromium (CrVI) in chrome plating, requiring authorization and phasing out its use.
- Main alternatives to hexavalent chrome for agricultural components include trivalent chromium (Cr(III)) plating, electroless nickel composites, and thermal spray coatings like HVOF, offering comparable wear/corrosion resistance with lower toxicity and regulatory compliance. These options reduce environmental risks from Cr(VI) while matching durability for farm stresses, though initial costs.

Chrome plating strengthens supply chain reliability by extending equipment life 2–10x, reducing downtime in peak seasons, and enabling premium pricing for high–performance machinery amid rising farm mechanization demands. (Ertani, A.et al, 2017; Malvajerdi, A. S., 2023; Mohapatra, G., & Sahay, S.S., 2017) Providers gain loyalty via technical support, custom racking, and regional facilities that cut shipping costs, positioning as top–tier finishers. Shift to trivalent chrome or hybrid processes counters hexavalent chromium regulations, enhancing eco–compliance while maintaining wear resistance for hydraulics and blades. Trivalent chromium plating replaces toxic hexavalent methods, offering lower environmental impact while maintaining durability and aesthetics.

Strategic perspectives focus on regulatory compliance, technological innovation, and adaptation to automotive and industrial demands. Threats include raw material price volatility, competition from alternative coatings, and stricter waste rules, necessitating R&D investment. Strategic focus on customization and sustainable practices positions firms for long–term competitiveness. Closed–loop recycling, energy–efficient tech, and hex–free alternatives address environmental concerns, boosting compliance and safety. Top technological innovations in chrome plating equipment focus on automation, sustainability, and precision control to enhance efficiency and compliance. These enhance performance in equipment like plows, aligning with circular economy goals in sustainable materials. Robotic systems provide real–time process monitoring, predictive maintenance, and waste reduction. Pulse plating and laser–assisted techniques improve adhesion, efficiency, and coating quality in high–volume operations. This linear, automated process integrates etching, plating, washing, and cooling, boosting throughput for hydraulic and agricultural components.

CONCLUSIONS

Chrome plating remains critical for agricultural equipment reliability in harsh conditions, where unprotected steel corrodes rapidly from fertilizers, pesticides, and abrasive soils. It minimizes downtime—vital for seasonal operations—boosting productivity and reducing repair costs by up to 50% on components like stripper plates and baler hooks. With market growth driven by mechanized farming in emerging regions, chrome (especially trivalent variants) supports sustainable equipment longevity amid regulatory shifts.

In agriculture, chrome plating prevents failures from abrasive grains, chaff, and fertilizers on components like baler hooks, stripper plates, and tillage tools, reducing lifecycle costs and downtime. It supports reliable performance under demanding conditions, enhancing productivity for over 80 years. Chrome plating delivers exceptional hardness (66–70 Rockwell C), wear resistance, and corrosion protection, extending equipment life by 40–100% while reducing friction and maintenance costs.

Key benefits of chrome plating can be summarized as follow:

- Superior hardness and durability: Increases surface hardness to 66–70 HRC without altering base material properties, resisting abrasion from crops, soil, and mechanical stress in agricultural tools like harvester blades and plows.

- Wear and corrosion resistance: Protects against rust, oxidation, and harsh chemicals (e.g., fertilizers causing 1,250 μm/year steel corrosion), ideal for humid fields and chemical exposure.
- Low friction and lubricity: Reduces seizing, galling, and energy use in moving parts like hydraulic cylinders and shafts, enabling smoother operation at lower temperatures.
- Uniform coverage on complex shapes: Electrochemical process deposits 2–250 μm thick layers evenly on irregular geometries, holes, and crevices, unlike line–of–sight sprays.
- Cost and downtime savings: Minimizes repairs, extends component life, and boosts productivity by keeping farm equipment operational longer during critical seasons.
- Easy maintenance: Smooth, non–porous finish resists buildup, simplifies cleaning, and restores worn parts to near–original dimensions.

Overall, chrome plating maximizes uptime by minimizing downtime during peak seasons, cutting repair costs through 2–10x lifespan extension on blades and hydraulics. It boosts productivity via smoother operation and lower friction, reducing energy use and enabling reliable performance in harsh conditions.
Key weaknesses of chrome plating for farm machinery parts include high costs, environmental/health hazards from hexavalent chromium, brittleness/porosity leading to cracking, and process–related defects like poor adhesion or blistering.

SWOT enhances strategic planning by uncovering hidden opportunities, mitigating risks early, and fostering proactive adaptations to change. Its simplicity makes it versatile for businesses, projects, or operations, promoting informed decisions and competitive advantages. In plating operations, such as chrome plating for agricultural equipment, SWOT evaluates internal factors like specialized expertise or outdated equipment (strengths/weaknesses) against external ones like regulatory shifts on chemicals or demand for sustainable coatings (opportunities/threats). This context–specific analysis guides process improvements, compliance strategies, and innovation in protective coatings, aligning with circular economy goals in materials engineering. Key strengths in plating operations include superior corrosion and wear resistance, enhanced durability, and cost–effective material enhancement for industrial applications like agricultural equipment. Plating operations excel in providing exceptional corrosion resistance against moisture, chemicals, and environmental degradation, extending component lifespan in harsh conditions. They also deliver high wear resistance through hard coatings. Precise control over coating thickness and microstructure ensures minimal distortion and tailored properties for complex geometries.

These operations restore worn parts dimensionally, minimizing downtime, and offer aesthetic finishes that add market value. In sustainable contexts, advancements align with eco–friendly practices, enhancing compliance and innovation in protective coatings. Threats in plating operations primarily stem from stringent environmental regulations, hazardous chemical use, and volatile raw material costs, posing risks to compliance and profitability. Wastewater contamination and chemical spills harm ecosystems, leading to legal liabilities and business interruptions from fires or equipment failures. Supply chain disruptions for hazardous materials amplify downtime in sectors like agricultural equipment manufacturing.

Under economical aspects, plating enables cost savings by using affordable base materials coated thinly with premium metals, reducing waste and replacement needs. Automation potential boosts efficiency, scalability, and throughput in manufacturing, supporting sectors like automotive and agriculture.

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PRELIMINARY RESEARCH ON SPERM QUALITY IN THE *SILURUS GLANIS* SPECIES / *CERCETĂRI PRELIMINARE PRIVIND CALITATEA SPERMEI LA SPECIA SILURUS GLANIS*

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ABSTRACT

The research aimed to evaluate the quality of European catfish (Silurus glanis) sperm under cryopreservation conditions, with a focus on the efficiency of different cryoprotectants, equilibration times and freezing volumes. Semen was collected from hormonally stimulated breeders and subjected to testing with dimethyl sulfoxide (Me_2SO), methanol and Me_2SO–propanediol combinations. The parameters analyzed after thawing were motility, viability and hatching rate.

The results showed that Me_2SO (8–12%) or the combination of Me_2SO + propanediol maintained high hatching rates (82–86%), comparable to the fresh control (87–88%). In contrast, methanol significantly reduced incubation success (53–63%). Post-thaw motility ranged between 50–61% for Me_2SO, 57% for Me_2SO + propanediol and only 20% for methanol, while fresh sperm showed 96% motility. The percentage of live sperm after thawing ranged between 7–19% for Me_2SO, 38% for Me_2SO + propanediol and 43% for methanol, compared with 92% in fresh sperm. Post-thaw motility was closely correlated with hatching rate ($r = 0.76$; $P < 0.001$), confirming motility as the main predictor of fertilization success.

These results demonstrate that Me_2SO-based cryoprotectants ensure the highest fertilization capacity in Silurus glanis sperm cryopreservation and provide an effective protocol for aquaculture and genetic resource conservation.

REZUMAT

Cercetările au avut ca obiectiv evaluarea calității spermei de somn european (Silurus glanis) în condiții de crioconservare, cu accent pe eficiența diferiților crioprotectori, a timpilor de echilibrare și a volumelor de congelare. Materialul seminal a fost colectat de la reproducători stimulați hormonal și supus testării cu dimetilsulfoxid (Me_2SO), metanol și combinații Me_2SO–propanediol. Parametrii analizați după decongelare au fost motilitatea, viabilitatea și rata de eclozare.

Rezultatele au arătat că Me_2SO (8–12%) sau combinația Me_2SO + propanediol au menținut rate de eclozare ridicate (82–86%), comparabile cu martorul proaspăt (87–88%). În schimb, metanolul a redus semnificativ succesul incubării (53–63%). Motilitatea post-decongelare a fost de 50–61% pentru Me_2SO, 57% pentru Me_2SO + propanediol și doar 20% pentru metanol, în timp ce sperma proaspătă a prezentat 96% motilitate. Procentul de spermatozoizi vii după decongelare a variat între 7–19% pentru Me_2SO, 38% pentru Me_2SO + propanediol și 43% pentru metanol, comparativ cu 92% la martorul proaspăt. Motilitatea post-decongelare s-a corelat strâns cu rata de eclozare ($r = 0,76$; $P < 0,001$), confirmând că aceasta este principalul indicator al succesului fecundării.

Aceste rezultate demonstrează că crioprotectorii pe bază de Me_2SO asigură cea mai bună capacitate de fertilizare în crioconservarea spermei la Silurus glanis și oferă un protocol eficient pentru acvacultură și conservarea resurselor genetice.

INTRODUCTION

The European catfish (*Silurus glanis*) is one of the most valuable freshwater fish species in European aquaculture due to its fast growth, high market demand and adaptability to intensive farming systems. However, intensive reproduction from a limited number of breeders may reduce genetic variability, increasing the risk of inbreeding and lowering population resilience. Therefore, maintaining genetic diversity in broodstocks is essential for sustainable production and disease resistance. Cryopreservation of sperm is widely recognized as a key tool for preserving aquatic genetic resources, supporting selective breeding

programs and establishing sperm banks for endangered or high-value species (*Labbé et al., 2017; Tiersch & Green, 2019; Yang & Tiersch, 2018*).In the last decade, major advances in fish reproductive biotechnology have focused on optimizing sperm cryopreservation protocols to improve post-thaw fertilization success. Numerous studies demonstrated that cryoprotectant type, extender composition, equilibration time and freezing rate directly influence sperm membrane integrity, motility and fertilizing capacity (*Asturiano et al., 2017; Cabrita et al., 2014; Martínez-Páramo et al., 2017*). In siluriform fishes, Me_2SO-based extenders have shown high efficiency in maintaining post-thaw sperm functionality, while methanol generally provides inferior fertilization results (*Viveiros et al., 2015; Ninhaus-Silveira et al., 2019*). Recently cryobiological research emphasizes the importance of species-specific protocol optimization, since sperm sensitivity to osmotic and thermal stress varies considerably among freshwater fish species (*Gwo et al., 2021; Linhart et al., 2022*). Controlled freezing systems and improved cryoprotectant combinations have significantly enhanced fertilization outcomes compared to early protocols, allowing reliable long-term storage of genetic material (*Linhart et al., 2022; Zhang et al., 2023*). Moreover, modern sperm quality assessment methods confirm that post-thaw motility remains the most reliable predictor of fertilization success in fish (*Martínez-Páramo et al., 2017; Cabrita et al., 2014*).

Although initial attempts at *Silurus glanis* sperm cryopreservation were reported decades ago, contemporary developments in extender formulation, equilibration management and freezing control now allow much higher reproducibility and efficiency. Recent studies also highlight growing interest in developing standardized cryopreservation protocols for *Silurus glanis* to support Eastern European aquaculture and conservation programs (*Popescu et al., 2024*).

MATERIALS AND METHODS

Research on sperm cryopreservation in *Silurus glanis* was conducted at the Fish Farming Research and Development Station, and for this purpose, an experimental group of 8 males and 4 females was formed. The experimental protocol for sperm analysis and quality assessment involved the following phases: selection of breeding males, hormonal stimulation, sperm sampling, and sperm quality assessment. The breeding fish were selected in July (Figure 1) and kept isolated in 4,000-liter tanks (Figure 2), ensuring a feed flow of 0.2 l/s at 22-23 °C. Before each injection and gamete collection, males and females were anesthetized in a 2-phenoxyethanol solution (1:1000). Spermatogenesis and ovulation were stimulated by intramuscular injection of carp pituitary (CP) at doses of 5 mg per kg of body weight. Sperm was collected 48 hours after CP stimulation.

The eggs were harvested after hormonal stimulation at 500-510 degree-hours from females, individually, grouped, stored for a short period at a temperature of 18-20°C, and used directly for the experiment. Before fertilization, four batches of approximately 1 g (approximately 150 eggs) were weighed weighed with an accuracy of 0.0001 g and fixed in 4% formaldehyde for subsequent counting to determine absolute fertility (number of eggs/female) and relative fertility (number of eggs/kg female). An average of 180,000 eggs were collected from one female catfish.

Fig. 1 - Selection of breeding stock for catfish

Fig. 2 - Basin for parking and maturing catfish spawners

Sperm collection and dilution

Sperm was collected by gentle abdominal pressure into sterile 250 ml containers containing immobilization solution (IS: 200 mM NaCl, 30 mM Tris-HCl, pH 7). This procedure prevented contamination with urine, which otherwise triggers premature activation of sperm motility. The dilution ratio between IS and spermatozoa was maintained at approximately 0.8:1. Samples were stored on ice (0–4 °C) until further processing. Only samples with motility >80% were selected.

The cryoprotectants tested included:

- Me_2SO (dimethyl sulfoxide): 8, 10, 12% (v/v);
- Methanol: 5, 7.5, 10% (v/v);
- Binary mixtures: Me_2SO + 1,2-propanediol, equal proportions (4–6% each).

The final mixtures were prepared by gently mixing the sperm diluted in isolation solution (IS) with a diluent containing cryoprotectant. The sperm samples were stored in a Dewar storage tank in liquid nitrogen (-196°C) (Figure 3).

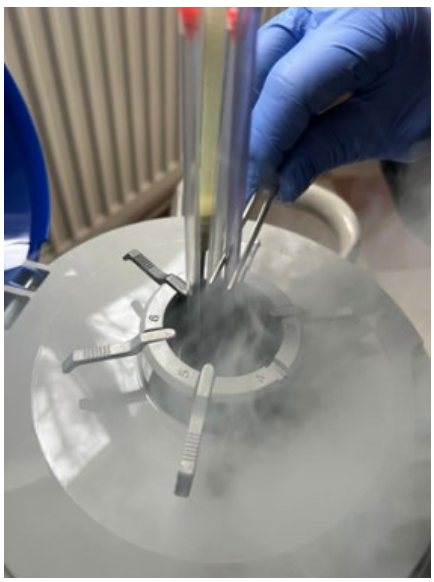

Fig.3 - Immersion of sperm samples in the Dewar storage tank

Freezing protocol

The samples were cryopreserved using a programmable freezer. The cooling stages were as follows:

1. From +4 °C to –9 °C at –4 °C/min

2. From –9 °C to –80 °C at –11 °C/min
3. Maintained at –80 °C for 6 minutes
4. Immersion in liquid nitrogen (–196 °C) for long-term storage.

Thawing procedure

The vials were thawed by immersion in a 40 °C water bath for 105 seconds with continuous agitation. Fresh semen stored at 0–4 °C served as a control.

Fertilization test

For fertilization studies, 5 g of oocytes (~145 eggs/g) were fertilized with thawed or fresh sperm, 2 ml/100 g. Activation was performed with 17 mM NaCl + 5 mM Tris-HCl (pH 8). Fertilized eggs were incubated in Nucet incubators. Incubation lasted 3 days, with an average temperature of 22.8°C.

Sperm quality assessment

Motility was assessed using a ZEISS Axio Vert 1 compact inverted microscope. The optical combination used for this control is a 10x eyepiece with a 20x and 40x objective, using a Burker grid slide. Motile spermatozoa (%) were evaluated 20 seconds after activation (Figure 4).

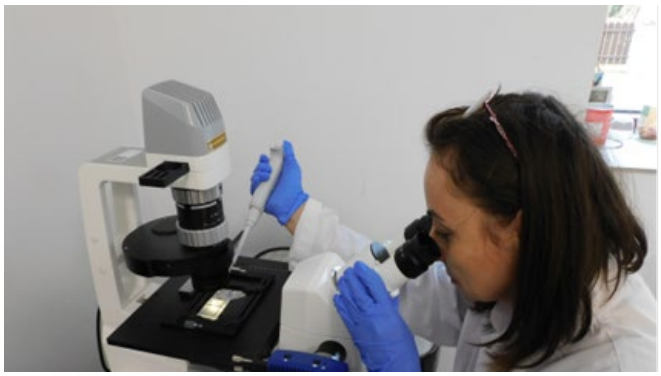

Fig.4 - Microscopic evaluation of sperm quality

Viability

Sperm viability was determined by assessing motility. This was performed using a compact phase-contrast microscope, with a 10X eyepiece and a 20X or 40X objective lens, using a grid slide (Burker). In general, sperm have a relatively short viability period after activation in water. Therefore, all preparations for the activation and dilution of sperm with water must be carried out before fertilization in the incubation station. Once the sperm has been activated, it must be used immediately, within a few seconds, otherwise the chances of achieving a good fertilization rate decrease dramatically.

Fertilization success: expressed as hatching rate (% of fertilized eggs that hatched).

Statistical analysis

All treatments were performed in triplicate. Results were expressed as mean ± standard deviation (SD). One-way ANOVA with Tukey's post-hoc test was used for comparison. Pearson correlation coefficients were calculated between sperm quality parameters and hatching rates. Statistical significance was set at $P < 0.05$.

RESULTS

Effect of cryoprotectants on hatching rate

Fresh sperm produced a hatching rate of 87–88%. Treatments with Me_2SO resulted in high post-thaw hatching success (82–86%), statistically similar to the fresh sperm sample. The binary mixture of Me_2SO and propanediol (5% each) also achieved a hatch rate >82%. In contrast, methanol treatments significantly reduced hatching, with values ranging from 53 to 63%. These findings confirm that Me_2SO is the most effective cryoprotectant for *S. glanis* sperm (Bart,1998, Cosson, 2000) (Table 1).

Table 1

Effect of cryoprotectants on the hatching rate in *Silurus glanis*

Cryoprotected	Hatching rate (%)
Me_2SO 8%	85
Me_2SO 10%	83
Me_2SO 12%	76
Me_2SO+Prop 5%+5%	82
Methanol 7.5%	53
Fresh control	87

Effect of cryoprotectants on the percentage of live sperm

Although Me_2SO ensured good fertility, the percentage of "live" sperm after thawing was relatively low (7–19%). The combination of Me_2SO + propanediol significantly improved viability (38%), and methanol even led to a value of 43%. However, fresh sperm remains clearly superior (92%). (Table 2).

Table 2

Effect of cryoprotectants on the percentage of live sperm

Cryoprotected	Live sperm (%)
Me_2SO 8%	7
Me_2SO 10%	17
Me_2SO 12%	19
Me_2SO +Prop 5%+5%	38
Methanol 7.5%	43
Fresh control	92

Effect of cryoprotectants on sperm motility

Post-thaw motility was 50–61% for Me_2SO, 57% for the combination with propanediol, and only 20% for methanol. Fresh sperm had 96%. (Table 3).

Motility is the strongest indicator of fertilization success, and treatments with Me_2SO and Me_2SO+prop are the most promising. Methanol proves to be ineffective from this point of view as well.

Table 3

Effect of cryoprotectants on sperm motility

Cryoprotected	Motility (%)
Me_2SO 8%	50
Me_2SO 10%	61
Me_2SO 12%	49
Me_2SO +Prop 5%+5%	57
Methanol 7.5%	20
Fresh control	96

Equilibration time on sperm quality

Equilibration time in cryopreservation practice is the time interval during which sperm is kept in contact with the cryoprotectant solution before undergoing the freezing process.

Shorter equilibration time (0–5 min) resulted in good hatching results (78–84%), but motility and viability were reduced. Longer equilibration (20 min) significantly increased motility (62%) and viability (58%), but the hatching rate decreased (74%) (Table 4).

Table 4

Effect of equilibration time on sperm quality

Balancing time (min)	Hatching rate (%)	Motility (%)	Live spermatozoa (%)
0	78	34	45
5	84	49	32
20	74	62	58
Fresh control	88	96	92

An average equilibration time (≈5 min) seems to ensure a good balance for the hatching rate, but for sperm quality (motility and viability) a longer time is beneficial (Figure 5).

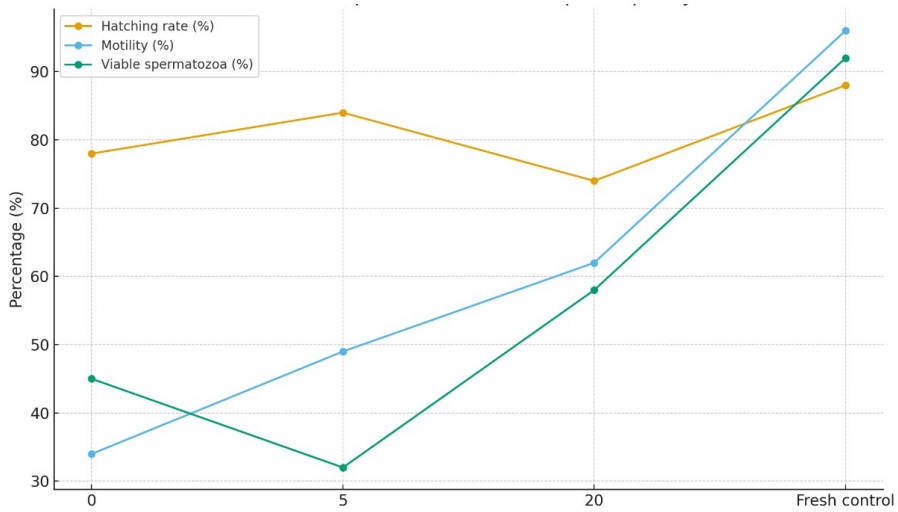

Fig. 5 - Effect of equilibration time on sperm quality

Effect of frozen volume on sperm quality

The hatching rate was higher at low and medium volumes (1–2 ml: 80–81%), but decreased at 4 ml (71%). Motility was better at 4 ml (51%), but viability was still low (20%). At low volumes, viability was extremely low (3% at 1 ml) (Table 5).

Table 5

Effect of frozen volume on sperm quality

Volume (ml)	Hatching rate (%)	Motility (%)	Live spermatozoa (%)
1	80	47	3
2	81	37	15
4	71	51	20
Fresh control	88	96	92

Small volumes ensure uniform cooling and a good hatching rate, but compromise viability. Large volumes partially protect the cells, increasing motility and viability, but reduce hatching success (Figure 6).

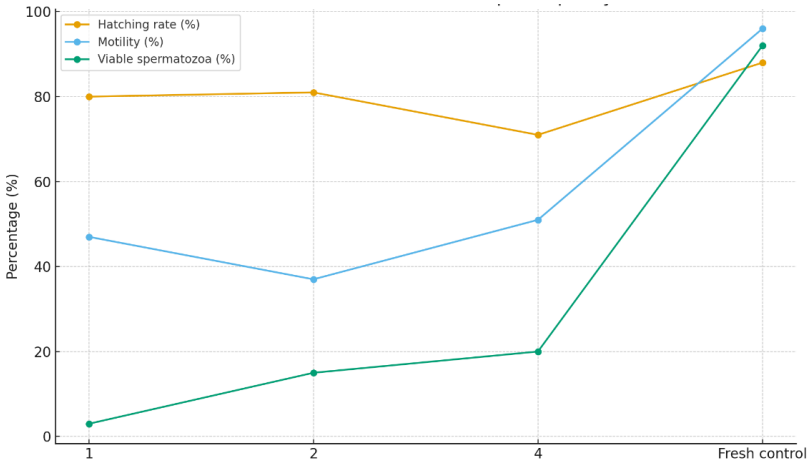

Fig. 6- Effect of frozen on sperm quality

CONCLUSIONS

Me_2SO (8–12%) is the most effective cryoprotectant for *Silurus glanis* sperm, maintaining hatching rates similar to the control. The combination of Me_2SO + propanediol is also promising. Methanol proved to be unsuitable.

Motility is the main indicator of fertilization success, with a close correlation with hatching rate, while simple cell viability is not sufficient to guarantee fertility.

Equilibration time directly influences sperm quality. A short time (≈5 min) optimizes the hatching rate, but a longer time (20 min) improves motility and viability. The choice depends on the final objective (yield vs. cell quality).

The freezing volume alters the balance between hatching success and sperm quality. A small volume (1–2 ml) increases the hatching rate but reduces viability, while larger volumes (4 ml) maintain better motility and viability but compromise incubation success.

Overall, the results demonstrate that cryopreservation of European catfish sperm is feasible and effective if the appropriate cryoprotectant is used and the technical parameters (equilibration time and volume) are optimized. These protocols can be successfully applied in aquaculture to maintain production and in the conservation of genetic resources to protect biological diversity.

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AUTOMATED PHEROMONE TRAP WITH AI RECOGNITION FOR APPLE ORCHARD PESTS: SYSTEM DESIGN, VALIDATION, AND CLIMATIC DATA INTEGRATION
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CAPCANĂ AUTOMATIZATĂ CU FEROMONI ȘI RECUNOAȘTERE PRIN INTELIGENȚĂ ARTIFICIALĂ PENTRU DĂUNĂTORII DIN LIVEZILE DE MĂR: PROIECTARE, VALIDARE ȘI INTEGRAREA DATELOR CLIMATICE

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Keywords: *automated trap; pheromones; artificial intelligence; pest monitoring; apple orchards*

ABSTRACT

This paper presents the design and development of an automated system for monitoring pests in apple orchards, based on pheromone traps integrated with artificial intelligence and climatic data acquisition. The proposed system includes a pheromone-based trap equipped with a digital camera, a processing unit, and a meteorological station, enabling automatic image capture and environmental data collection. Computer vision algorithms are employed for insect identification, while the software architecture supports data storage and analysis. The system is intended to support integrated pest management strategies and precision agriculture by providing continuous and objective pest monitoring under field conditions.

REZUMAT

Lucrarea prezintă proiectarea și dezvoltarea unui sistem automatizat pentru monitorizarea dăunătorilor din livezile de măr, bazat pe capcane cu feromoni integrate cu inteligență artificială și achiziția datelor climatice. Sistemul propus include o capcană echipată cu cameră digitală, o unitate de procesare și o stație meteorologică, permițând capturarea automată a imaginilor și colectarea parametrilor de mediu. Algoritmii de viziune artificială sunt utilizați pentru identificarea insectelor, iar arhitectura software facilitează stocarea și analiza datelor, oferind suport pentru strategiile de management integrat al dăunătorilor și agricultura de precizie.

INTRODUCTION

Plant protection in apple orchards represents a critical component of sustainable fruit production systems, directly affecting yield, fruit quality, production costs, and environmental impact. Apple orchards are perennial agroecosystems characterized by recurrent pest pressure and complex ecological interactions, which require long-term, data-driven management strategies. In this context, Integrated Pest Management (IPM) has been established as the dominant framework in modern plant protection, combining monitoring, economic thresholds, biological control, and rational chemical interventions. The historical development and consolidation of IPM as a scientific concept were comprehensively described by Kogan (*Kogan M., 1998*), who emphasized the transition from reactive pest control toward ecologically based decision-making.

Among the economically important pests of apple, the codling moth (Cydia pomonella L.) remains a key target species worldwide due to its direct impact on fruit quality and its ability to develop resistance to insecticides. Extensive research has highlighted the importance of pheromone-based monitoring and mating disruption as core components of codling moth management programs [15]. Accurate monitoring of adult flight dynamics is essential for timing control measures; however, conventional pheromone trap inspection relies largely on manual counting, which is labor-intensive, time-consuming, and subject to observer variability.

The increasing adoption of precision agriculture technologies has stimulated the development of automated pest monitoring systems capable of providing continuous and objective data. Camera-equipped pheromone traps have emerged as a promising solution for improving temporal resolution and reducing labor requirements. A comprehensive review by Preti et al. (*Preti et al., 2021*) analyzed the strengths and limitations of such systems, emphasizing their potential for remote monitoring while also identifying challenges related to image quality, insect overlap, and robustness under field conditions. Similar

approaches based on optical and electronic sensors have been proposed for large-scale insect surveillance, highlighting the role of digital technologies in modern pest management. (*Skendzic et al., 2021*)

Parallel to advances in sensing hardware, artificial intelligence (AI) and deep learning techniques have enabled significant progress in automated insect detection and identification. Vision-based systems for counting and recognizing flying insects have demonstrated the feasibility of automated image analysis in agricultural applications (*Van der Werf et al., 2007*). Convolutional neural networks (CNNs) have been shown to achieve high accuracy in insect recognition tasks when trained on appropriately labeled datasets. Moreover, automated taxonomic identification using feature transfer from CNNs has reached expert-level performance, supporting the applicability of AI in entomological monitoring (*Zhong et al., 2018*).

In apple orchards, the interpretation of pest monitoring data must also consider the strong influence of climatic conditions on insect development and population dynamics. Temperature plays a central role in regulating insect growth rates, survival, and reproduction, and temperature-based phenological models are widely used in pest management. Regnière et al. (*Regniere et al., 2012*) provided a detailed synthesis of temperature effects on insect development and modeling approaches used in applied entomology. Beyond seasonal variability, climate change further complicates pest management by altering voltinism, geographic distribution, and damage intensity. Studies have shown that rising temperatures can significantly increase crop losses caused by insect pests (*Deutsch et al., 2018)*, while reviews focused on agricultural systems emphasize the need to integrate climatic data into pest monitoring strategies (*Preti et al., 2021*).

Consequently, effective pest monitoring in apple orchards requires an integrated technological approach that combines pheromone-based specificity, automated image acquisition, AI-based insect recognition, and climatic data collection. Such systems can provide timely and objective information to support IPM strategies and precision agriculture. In this context, the present study focuses on the design of an automated pheromone trap system incorporating artificial intelligence and climatic data acquisition, with emphasis on the hardware–software architecture and data integration framework required for orchard pest monitoring.

MATERIALS AND METHODS

The methodology applied in this study aimed at the development and configuration of an autonomous system for monitoring pests in apple orchards, based on pheromone trapping, standardized photo acquisition, readiness for automated recognition using artificial intelligence, and the integration of local climatic data. The main objective of this approach was to provide a coherent description of the materials used and of the stages of assembly, wiring, configuration, and field operation, so that the system can deliver, without frequent human intervention, synchronized datasets consisting of: (1) images of the adhesive surface inside the trap and (2) meteorological parameters relevant to insect population dynamics. The system was built on a modular architecture composed of an automated weather station - Fig. 1 (1.), a smart pheromone trap equipped with a digital camera and LED illumination, an electronic acquisition and control module, an autonomous power supply based on a photovoltaic panel and battery Fig. 1 (2.), and a mechanical support structure for orchard installation. The modular design allows field deployment of the components at functional heights that are accessible for maintenance, while protecting the electronic equipment from direct contact with soil and moisture. The system was designed to automatically collect data from two main sources: environmental parameters measured by the weather station and images acquired inside the pheromone trap, which can subsequently be processed using visual analysis algorithms for the detection and classification of captured insects.

The weather station was assembled by integrating standardized industrial components mounted on a vertical anodized aluminum support, selected for its mechanical stability and corrosion resistance. The sensor configuration included an anemometer for wind speed measurement, a wind vane for wind direction determination, a rain gauge for precipitation quantification, an air temperature and relative humidity sensor (T/RH), and a solar radiation sensor (pyranometer) for estimating light intensity. These elements were positioned to reduce local interference effects (obstacles, turbulence, shading) and to accurately reflect the orchard microclimate. The selected parameters are considered essential for interpreting insect flight activity and pest phenology.

Fig.1. 1. Weather station – Automated weather station installed in the apple orchard, equipped with sensors for air temperature and relative humidity, wind speed (anemometer), wind direction (wind vane), precipitation, and solar radiation. 2. Smart pest trap – Intelligent pheromone-based pest trap mounted at canopy level, designed for monitoring orchard pests. The trap integrates a pheromone lure, an internal adhesive capture surface, a digital camera for automatic image acquisition, and an LED illumination system

The smart pheromone trap represented the central component for pest monitoring and was designed to capture target insects (particularly Lepidoptera and Diptera) and to enable automatic image acquisition of insects retained on the adhesive surface. The trap operates based on the principle of pheromone attraction, using a centrally positioned pheromone compartment to ensure uniform diffusion of the attractant. The trap construction includes a lightweight and durable plastic main body with UV protection, a mounting and suspension system for stable installation, and an internal imaging zone designed to ensure a reproducible camera field of view between capture cycles. The HD digital camera is connected to the local processing/acquisition module, while image consistency under variable natural lighting conditions is enhanced through an integrated LED illumination system that is automatically activated during image capture, providing uniform and temporally comparable images.

From a connectivity perspective, the trap is coupled to the acquisition unit via a dedicated cable for power and data transmission, ensuring stable outdoor operation and reducing the risk of accidental disconnection. Captured images are stored locally and subsequently transmitted to the analysis platform. The information flow is designed to allow both periodic transmission and temporary local storage when network connectivity is unavailable. This approach is particularly relevant for orchard environments, where connectivity may vary due to terrain, vegetation, or mobile network coverage.

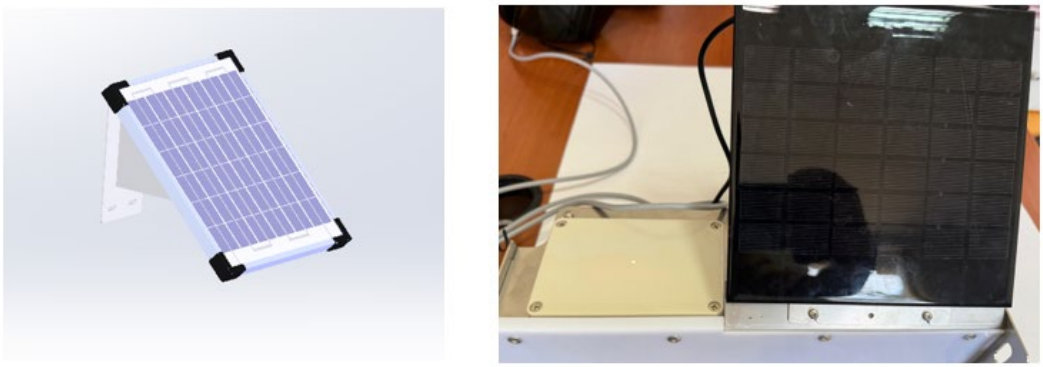

Fig. 2. Autonomous power supply

The autonomous power supply Fig. 2 system was implemented using a photovoltaic panel, a charge controller, and a battery, with the aim of ensuring continuous operation without connection to the electrical grid.

The photovoltaic panel used was a 50 W monocrystalline module, mounted on an adjustable metal support and oriented for optimal energy efficiency during the operating period. The generated energy is stored in a battery and distributed to the electronic modules, ensuring operation during periods of reduced solar radiation. In the implemented configuration, a 12 Ah battery was used, dimensioned to support the acquisition cycles of both sensors and camera, as well as communication requirements.

Mechanical integration of the components was achieved using a modular metal structure made of aluminum profiles. This structure allows the weather station to be mounted at an appropriate height, the smart trap to be fixed at an adjustable distance from the support axis, and the electronic equipment to be placed in areas protected from direct splashing or moisture. The support solution includes adjustable fastening elements that allow the inclination angle and position of the trap to be set, while also providing stability under wind and vibration loads. Figure 3 illustrates the final integrated configuration of the monitoring system installed in the apple orchard. The assembly includes the automated weather station mounted on the upper section of the support structure, the smart pheromone-based pest trap positioned at canopy level, the electronic acquisition and control module, and the autonomous photovoltaic power supply. All components are mechanically and functionally integrated on a modular metal stand, ensuring stable operation under field conditions and enabling simultaneous acquisition of climatic data and pest monitoring information.

Fig.3. Fully integrated experimental model – overall view

The electronic acquisition and control module was used as the command element for the entire system. It manages signals from the meteorological sensors, coordinates image capture within the trap and activation of the LED illumination, monitors energy levels, and handles the transmission of collected data. Fig. 3 For field use, the module was housed in an IP65-rated protective enclosure to ensure sealing against dust and moisture, reducing the risk of malfunction under rain, condensation, or dust generated by agricultural activities. Communication with the data platform was ensured through wireless interfaces (Wi-Fi/4G, or LoRa depending on configuration), combined with local storage and retransmission logic to minimize data loss. The integration process followed an operational sequence designed to reduce the risk of component damage and to facilitate step-by-step functional verification. Mechanical assembly included fixing the upper arm for meteorological sensors, the lateral arm for the trap, the protective enclosure for the acquisition module, and the solar panel onto the support structure. Electrical wiring and connections were carried out using properly dimensioned cables protected in UV-resistant flexible conduits, with short routing paths and intermediate fixation points to reduce

mechanical stress. Separate connections were implemented for the energy chain (panel–controller–battery) and for consumers (acquisition module, sensors, camera, and LED illumination).

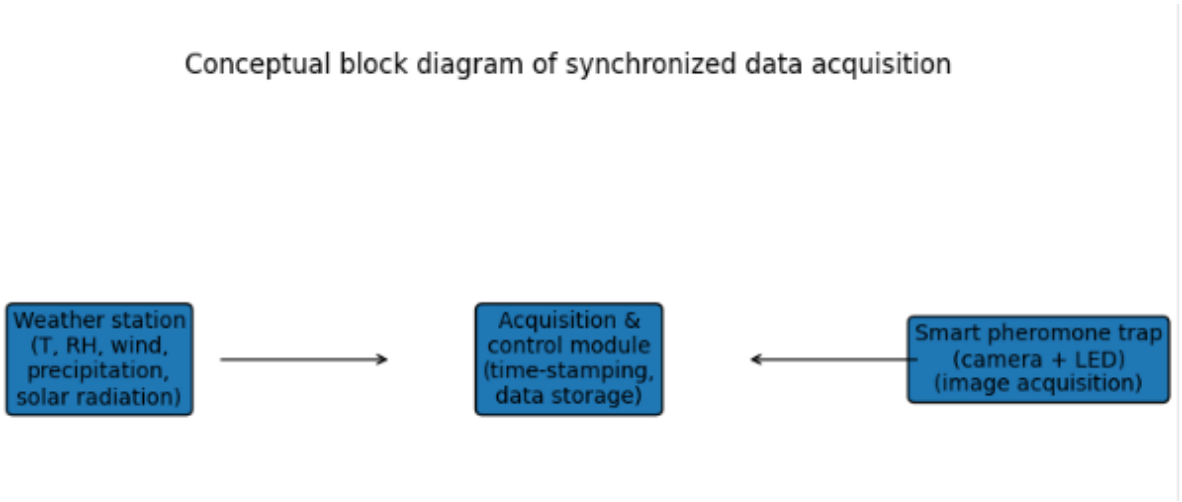

Fig. 4. Conceptual Block diagram of sincronized data acquisition

During the software configuration stage, the acquisition module was set to synchronize measurement and data transmission cycles. Distinct acquisition intervals were defined for the two data streams: meteorological parameters were recorded periodically, while photo captures were scheduled less frequently to limit energy consumption and data volume, while still maintaining a useful temporal resolution for monitoring. An example configuration included meteorological acquisition every 30 minutes and photo captures every 6 hours, with data transmission to the server every 12 hours. These parameters can be adjusted depending on pest pressure intensity and seasonal conditions.

Table 1

Data acquisition parameters applied for meteorological and image-based monitoring

Data type	Measured / acquired parameter	Acquisition interval	Purpose
Meteorological data	Air temperature, relative humidity	30 min	Monitoring microclimate influencing pest development
Meteorological data	Wind speed and direction	30 min	Characterization of conditions affecting insect flight
Meteorological data	Precipitation	30 min	Assessment of environmental constraints on pest activity
Meteorological data	Solar radiation	30 min	Evaluation of light and thermal conditions
Image data	Trap interior images	6 h	Documentation of insect captures for AI-based analysis
Data transmission	All datasets	12 h	Periodic synchronization with the digital platform

Calibration of the meteorological sensors aimed to verify correct operation and consistent response of each transducer through comparison with a reference weather station installed at the same location. This procedure was used to identify potential mounting deviations (e.g., shading, local turbulence, improper positioning) and to adjust reading or interpretation parameters where necessary. In parallel, for the imaging subsystem, camera alignment and illumination parameters were adjusted so that the adhesive surface was fully captured with sufficient clarity for subsequent identification, while LED lighting ensured uniformity and repeatability between image captures.

The data flow was designed to combine meteorological information and trap images within a single temporal framework. Environmental data (temperature, humidity, wind, solar radiation, precipitation) are periodically acquired by the weather station and transmitted to the acquisition module, where they are time-stamped and prepared for transmission. Similarly, the trap collects insects on the adhesive surface, and the

camera captures images at predefined intervals; these images are associated with the same timestamp system to enable subsequent automatic correlation with climatic variables.

Figure 5 presents a theoretical graphical representation of the data acquisition program implemented in the monitoring system. Meteorological parameters (air temperature, relative humidity, wind speed and direction, precipitation, and solar radiation) are acquired at high temporal resolution (every 30 minutes), ensuring continuous characterization of orchard microclimatic conditions. Image acquisition inside the smart pheromone trap is performed at lower frequency (every 6 hours), reflecting the dynamics of insect capture while limiting energy consumption and data volume. All datasets are periodically transmitted to the digital platform at 12-hour intervals. The schematic representation highlights the coexistence of multiple acquisition frequencies and their synchronization within a common temporal framework.

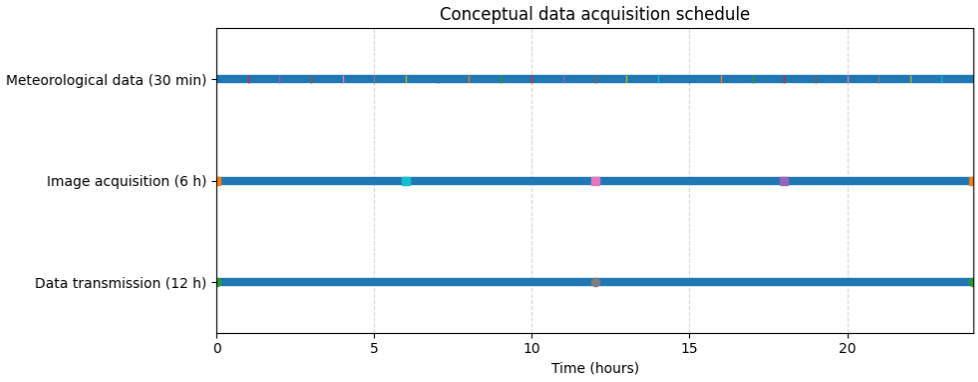

Fig. 5. Conceptual data aquizition schedule

For use within an AI workflow, the images are considered inputs for a visual processing pipeline that may include preprocessing (normalization, noise reduction, exposure correction), object detection (insects), and species classification, depending on the training dataset and the selected model. The described architecture allows the software recognition component to be updated without structural modifications, provided that input requirements (resolution, field of view, illumination) are maintained.

RESULTS

The experimental deployment of the integrated monitoring system demonstrated that the proposed configuration is suitable for continuous operation in apple orchard conditions and fulfills the functional objectives related to pest and climatic data acquisition. From a mechanical perspective, the modular support structure ensured adequate stability and resistance to environmental stressors, such as wind and variable weather conditions, while maintaining correct positioning of both the weather station and the smart pheromone trap. The use of corrosion-resistant materials and sealed enclosures contributed to the reliable protection of electronic components against moisture, dust, and temperature fluctuations. The weather station subsystem provided consistent and coherent measurements of key microclimatic parameters, including air temperature, relative humidity, wind speed and direction, precipitation, and solar radiation. These variables are recognized as major drivers of insect development and flight activity in orchard ecosystems. The recorded data showed stable temporal trends and were suitable for use in correlating pest presence with environmental conditions, supporting phenological interpretation and decision-making processes within integrated pest management frameworks.

The smart pheromone trap operated effectively as the central biotic monitoring component. The pheromone-based attraction mechanism ensured selective capture of target pest groups, while the internal adhesive surface allowed reliable retention of insects for imaging. The integrated digital camera, combined with automatic LED illumination, generated clear and uniform images under varying ambient light conditions. This consistency is essential for downstream image analysis and artificial intelligence–based recognition, as it reduces variability caused by shadows, glare, or insufficient contrast. The photovoltaic power supply, together with the battery storage, was sufficient to sustain the operation of sensors, imaging, and communication modules over extended periods, including intervals with reduced solar radiation. This confirms the suitability of the selected acquisition intervals and power management strategy for off-grid agricultural applications.

From a data management perspective, the synchronized acquisition of meteorological measurements and trap images enabled the creation of integrated datasets with a common temporal reference. Such datasets are particularly valuable for analyzing pest dynamics in relation to climatic conditions and for supporting predictive or AI-assisted monitoring approaches.

CONCLUSIONS

The developed monitoring system demonstrates the feasibility of integrating a smart pheromone-based pest trap with an automated weather station into a single, autonomous platform suitable for deployment in apple orchards. The modular design and robust mechanical integration allow reliable operation under field conditions, while protecting sensitive electronic components from environmental stress factors. The use of standardized industrial elements and renewable energy supply contributes to system stability and low maintenance requirements.

The combination of pheromone trapping and automated image acquisition provides a non-invasive and selective approach for monitoring key orchard pests. The consistent image quality ensured by the integrated camera and LED illumination represents an important prerequisite for the application of artificial intelligence techniques in insect detection and identification. At the same time, the continuous acquisition of local climatic parameters offers essential contextual information for interpreting pest dynamics and supporting integrated pest management strategies.

Energy autonomy achieved through the photovoltaic power system enables long-term, off-grid operation, which is critical for practical agricultural applications. Furthermore, the synchronized collection of biotic and abiotic data establishes a solid foundation for advanced data analysis, including the development of predictive models and decision-support tools.

The results indicate that the proposed system represents a robust and scalable solution for automated pest monitoring in apple orchards, providing a solid technical basis for further validation and extended field application.

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IMPACT OF CERTAIN AGRICULTURAL PRACTICES ON SEED AND BIOMASS YIELD IN MONOECIOUS HEMP (*CANNABIS SATIVA* L.) UNDER ARDS SECUIENI EXPERIMENTAL CONDITIONS

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IMPACTUL UNOR PRACTICI AGRICOLE ASUPRA PRODUCȚIEI DE SĂMÂNȚĂ ȘI BIOMASĂ LA CÂNEPA MONOICĂ (CANNABIS SATIVA L.), ÎN CONDIȚIILE EXPERIMENTALE DE LA SCDA SECUIENI

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ABSTRACT

The aim of the study was to evaluate the effect of sowing time and cutting type on yield components, physiological response, and quality characteristics of monoecious hemp (Cannabis sativa L.), under the pedoclimatic conditions of ARDS Secuieni, in 2025. The experiment was conducted using a bifactorial design, arranged in split plots with three replications, including two sowing times and three cutting types. The results showed that cutting type significantly influenced biomass and seed yield, with the highest values recorded in the two-cut variant: 7813 kg·ha⁻¹ fresh inflorescences, 1967 kg·ha⁻¹ dry inflorescences, and 2962 kg·ha⁻¹ seeds. In contrast, sowing time had a limited effect, being significant only for dry inflorescences yield. Regarding quality characteristics, sowing time did not significantly affect the analyzed parameters, whereas cutting type influenced total soluble solids and titratable acidity. The results highlight the importance of optimizing the cutting regime in relation to sowing time in order to increase productivity and improve quality characteristics in hemp, with the $E_1 \times C_2$ variant showing superior performance.

REZUMAT

Scopul cercetării a fost evaluarea efectului epocii de semănat și al tipului de retezare asupra componentelor de producție, răspunsului fiziologic și caracteristicilor de calitate la cânepa monoică (Cannabis sativa L.), în condițiile pedoclimatice de la SCDA Secuieni, în anul 2025. Experimentul a fost organizat după un design bifactorial, în parcele divizate, cu trei repetiții, incluzând două epoci de semănat și trei tipuri de tăiere. Rezultatele au arătat că tipul de retezare a influențat semnificativ producția de biomasă și de semințe, cele mai ridicate valori fiind înregistrate în varianta cu două tăieri: 7813 kg·ha⁻¹ inflorescențe proaspete, 1967 kg·ha⁻¹ inflorescențe uscate și 2962 kg·ha⁻¹ semințe. Prin comparație, epoca de semănat a exercitat un efect redus, semnificativ doar în cazul producției de inflorescențe uscate. În ceea ce privește caracteristicile de calitate, epoca de semănat nu a influențat semnificativ parametrii analizați, în timp ce tipul de tăiere a influențat substanța uscată solubilă și aciditatea titrabilă. Rezultatele evidențiază importanța regimului de retezare în corelație cu epoca de semănat, în vederea creșterii productivității și îmbunătățirii caracteristicilor de calitate la cultura de cânepă, varianta $E_1 \times C_2$ evidențiindu-se prin performanțe superioare.

INTRODUCTION

Hemp (*Cannabis sativa* L.) is one of the oldest cultivated species, having long been used for both fiber production and seeds, as well as for other food-related purposes (Van der Werf, 1991; Ranalli, 1999; Callaway, 2004). In recent decades, interest in this crop has been renewed due to its multifunctional character and its potential to provide renewable raw materials for sectors such as textiles, composite

materials, food, construction, and bioenergy (Schluttenhofer and Yuan, 2017; Ahmed et al., 2022; Visković et al., 2023).

The versatility of hemp is reflected in the wide range of products that can be obtained from its different plant parts. Fibers are used in textile products and composite materials, seeds have high nutritional value and are of interest for the development of food ingredients, while biomass and by-products can be exploited for energy purposes and other bio-based applications (Farinon et al., 2020; Parvez et al., 2021; Rehman et al., 2021; Burton et al., 2022).

From an agronomic point of view, hemp is characterized by adaptability and by the possibility of utilizing the whole plant; however, crop performance remains strongly influenced by the interaction between genotype, environment, and cultivation technology (Amaducci et al., 2015; Rehman et al., 2021; Visković et al., 2023). Among the technological factors, sowing time plays a major role because it conditions growth rate, plant height, biomass accumulation, and, in certain production systems, fiber quality (Halker et al., 2024; Myers et al., 2025). This relationship is closely linked to hemp's sensitivity to photoperiod, since the timing of flowering is influenced by day length and has direct consequences for crop adaptation to different environmental conditions and for productive potential (Amaducci et al., 2015; Zhang et al., 2021).

Sowing at the optimal time allows the extension of the vegetative phase and promotes biomass accumulation, particularly in crops intended for fiber production (Cosentino et al., 2012; Amaducci et al., 2015). In contrast, delayed sowing accelerates the transition to the reproductive phase and leads to reduced yields (Adamovics et al., 2017; Halker et al., 2024). In addition, sowing time may influence product quality through structural and biochemical changes (Amaducci et al., 2015).

In addition to sowing time, interventions applied to plants can influence growth patterns and biomass distribution. Removal of the apical meristem or cutting practices may reduce apical dominance and stimulate lateral shoot development, with effects on final yield depending on the biological material and the intended production objective (Ačko et al., 2019; Massuela et al., 2022).

In this context, analyzing the effects of sowing time and cutting practices on hemp development, productivity, and quality parameters is essential for optimizing cultivation technology, particularly under the challenges imposed by current climate change, to ensure stable yields adapted to different end uses.

MATERIALS AND METHODS

The research was conducted in 2025, within a bifactorial experiment organized using a split-plot design, with three replications. The experiment was established in the technological field of the Agricultural Research and Development Station Secuieni. The biological material used was a monoecious hemp variety developed and registered by ARDS Secuieni.

The experimental factors analyzed were Factor A – sowing time, with two levels [a_1 – epoch I (the first decade of May); a_2 – epoch II (the second decade of May)]; Factor B – cutting type, with three levels (b_1 – no cutting, b_2 – one cut, b_3 – two cuts).

The experiment was conducted on a soil with moderate N supply (IN: 3.50), very high P (corrected PAL: 333.94 mg/kg) and K (KAL: 409.19 mg/kg) contents, and high levels of Mg (366.70 mg/kg), mobile S (28.65 mg/kg), Fe (59.05 mg/kg), Cu (3.93 mg/kg), and Zn (3.63 mg/kg). Organic C (1.55%) and humus (2.67%) contents were moderate. The soil was slightly acidic (pH 6.72) and non-saline.

Sowing was carried out by using a mechanical seed drill, at a row spacing of 70 cm. During the growing season, four hoeing operations (two manual and two mechanical) were carried out, as well as one and two cuttings of the hemp plants, respectively, in accordance with the experimental design, in order to stimulate branching, following the Secuieni cultivation method (Popa et al., 2021).

The evolution of the main meteorological parameters during the growing season, namely air temperature and precipitation, is illustrated in the figures below.

The determinations performed on the experimental hemp variants included biomass yield (fresh and dry inflorescences) and seed yield, as well as quality parameters, namely vitamin C content, total soluble solids, titratable acidity, and pH, together with the chlorophyll content index, used as a physiological indicator. The data obtained were subjected to statistical analysis using two-factor ANOVA, and differences between means were evaluated using Duncan's test at a significance level of $p < 0.05$.

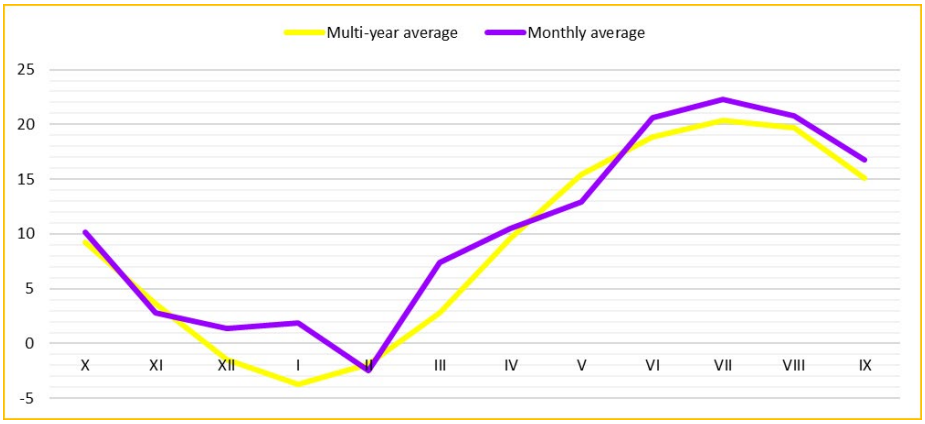

Fig. 1. Air temperature at ARDS Secuieni, during the 2024–2025 agricultural year

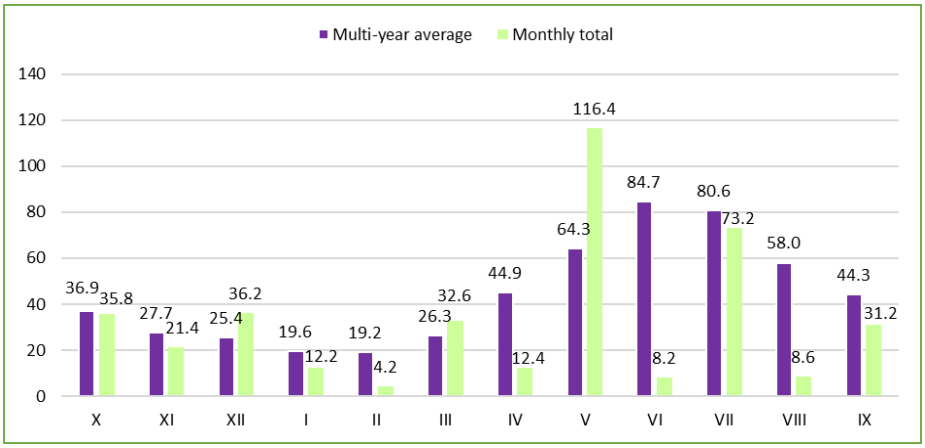

Fig. 2. Precipitation regime at ARDS Secuieni, during the 2024–2025 agricultural year

RESULTS AND DISCUTIONS

The individual and combined effects of sowing time and cutting type on fresh and dry inflorescences yield, seed yield, quality parameters, and the chlorophyll content index (CCI) in hemp are presented in the tables and figures below.

The results obtained highlight differentiated effects of sowing time and cutting type on the yield of inflorescences (fresh and dry) and seeds, as shown in Table 1.

Table 1

Effect of sowing time and cutting type on inflorescences and seed yield in hemp

Variant	Fresh inflorescences yield (kg·ha^{-1})	Dry inflorescences yield (kg·ha^{-1})	Seed yield (kg·ha^{-1})
Sowing time			
E_1	6714 ± 214	1894 ± 57	2839 ± 107
E_2	6100 ± 139	1622 ± 52	2608 ± 180
Significance	*ns*	*	*ns*
Cutting type			
NC	4758 ± 40 c	1425 ± 14 b	2776 ± 181 ab
C_1	6650 ± 238 b	1883 ± 92 a	2432 ± 140 b
C_2	7813 ± 350 a	1967 ± 82 a	2962 ± 108 a
Significance	*	*	*

E_1 - epoch I, E_2 - epoch II, NC - no-cutting, C_1 - one cut, C_2 - two cuts; Values are presented as mean ± standard error (SE). Within each column, ns - no statistically significant difference, * - statistically significant difference, values associated to different letters are significantly different according to Duncan's test at $p<0.05$.

Regarding sowing time, the E_1 variant recorded higher values for all three yield components (fresh inflorescences, dry inflorescences, and seeds) compared to E_2; however, the differences were statistically

significant only for dry inflorescences. These results suggest that sowing time particularly influences dry biomass production, without significantly affecting seed yield.

In terms of the cutting factor, a significant effect was observed on all analyzed yield parameters. Fresh inflorescences yield showed an increasing trend from the no-cutting variant (4758 kg·ha^{-1}) to one cut (6650 kg·ha^{-1}) and two cuts (7813 kg·ha^{-1}), with statistically significant differences among variants.

A similar pattern was observed for dry inflorescences yield, where C_1 (1883 kg·ha^{-1}) and C_2 (1967 kg·ha^{-1}) recorded significantly higher values compared to NC (1425 kg·ha^{-1}), with no significant differences between them, both being classified within the same statistical group.

Regarding seed yield, C_2 recorded the highest values (2962 kg·ha^{-1}), being significantly higher than C_1 (2432 kg·ha^{-1}), but not significantly different from NC (2776 kg·ha^{-1}).

Overall, the results indicate that the cutting type is a key technological factor for optimizing yield, particularly for inflorescences, while the influence of sowing time is less pronounced and limited to specific yield components.

The analysis of the interaction between sowing time and cutting type revealed significant effects on all analyzed yield parameters, indicating that crop response depends on the combination of the two factors, as shown in the table below.

Table 2

Effect of the interaction between sowing time and cutting type on inflorescences and seed yield in hemp

Variant	Fresh inflorescences yield (kg·ha^{-1})	Dry inflorescences yield (kg·ha^{-1})	Seed yield (kg·ha^{-1})
E_1 x NC	4867 ± 108 c	1467 ± 26 cd	2876 ± 134 ab
E_1 x C_1	7250 ± 200 a	2083 ± 67 a	2489 ± 118 b
E_1 x C_2	8027 ± 539 a	2133 ± 101 a	3152 ± 78 a
E_2 x NC	4650 ± 36 c	1383 ± 23 d	2676 ± 228 ab
E_2 x C_1	6050 ± 275 b	1683 ± 117 bc	2376 ± 177 b
E_2 x C_2	7600 ± 173 a	1800 ± 64 b	2772 ± 139 ab
Significance	*	*	*

E_1 - epoch I, E_2 - epoch II, NC - no-cutting, C_1 - one cut, C_2 - two cuts; Values are presented as mean ± standard error (SE). Within each column, * - statistically significant difference, values associated to different letters are significantly different according to Duncan's test at $p<0.05$.

Regarding fresh inflorescences yield, the highest values were recorded in the two cuts variant, regardless of sowing time, namely $E_1 \times C_2$ (8027 kg·ha^{-1}) and $E_2 \times C_2$ (7600 kg·ha^{-1}), with no significant differences between them. However, E_1 produced higher values compared to E_2. The variant NC, regardless of sowing time, recorded the lowest yields, highlighting the important role of cutting in biomass accumulation under the growing conditions of 2025.

For dry inflorescences yield, the $E_1 \times C_2$ variant recorded the highest value (2133 kg·ha^{-1}), with no significant differences compared to $E_1 \times C_1$ (2083 kg·ha^{-1}), both being classified within the same statistical group. For sowing time E_2, increasing the number of cuttings resulted in a non-significant yield increase of 117 kg·ha^{-1}, from 1683 kg·ha^{-1} ($E_2 \times C_1$) to 1800 kg·ha^{-1} ($E_2 \times C_2$). The no-cutting variants (NC) showed the lowest dry inflorescences yields, with the minimum value recorded in E_2 (1383 kg·ha^{-1}).

Regarding seed yield, the highest value was recorded by the $E_1 \times C_2$ variant (3152 kg·ha^{-1}), which was significantly higher than most of the other combinations. It is noteworthy that, under E_1 conditions, the application of two cuttings had a positive effect on seed yield, whereas a single cutting ($E_1 \times C_1$) resulted in a significant decrease (2489 kg·ha^{-1}). For sowing time E_2, the differences among cutting variants were less evident statistically, with most variants classified within group *ab*, indicating reduced variability in seed yield. However, the overall yield level was lower than that obtained in $E_1 \times C_2$.

Sowing time had a significant effect on the CCI, with statistically significant differences between the variants (Figure 3). Higher values were recorded for E_1 (43.1) compared to E_2 (34.9).

Cutting type significantly influenced CCI, with higher values recorded in the no-cutting variant (43.3), showing significant differences compared to the cut variants. The C_1 (38.2) and C_2 (35.5) variants did not differ significantly from each other.

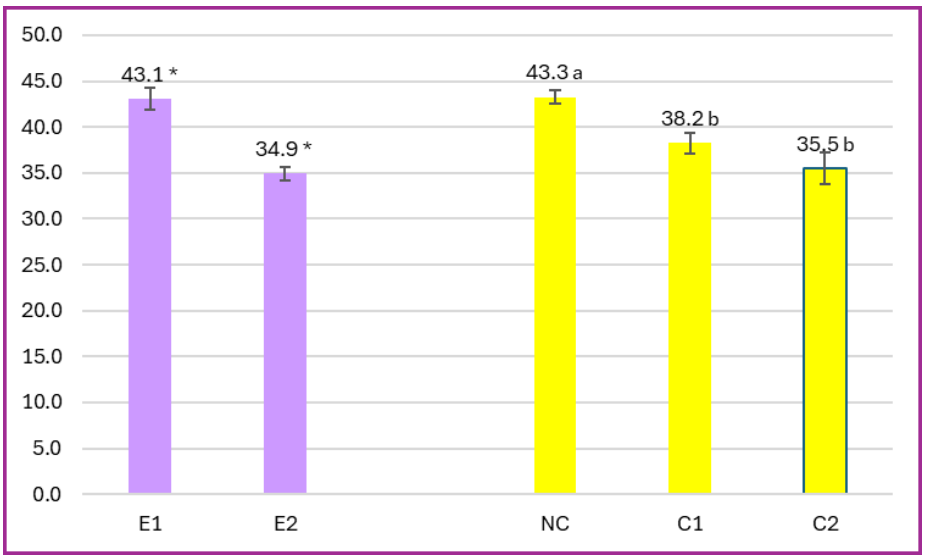

Fig. 3. Chlorophyll content index (CCI) values in hemp as affected by sowing time and cutting type

The interaction between sowing time and cutting type significantly influenced CCI, as shown in Figure 4. The highest values were recorded under E_1, regardless of cutting type (E_1 × NC: 45.6, E_1 × C_1: 43.4, E_1 × C_2: 40.2), with no significant differences among these variants. In contrast, under E_2, CCI values were significantly lower in the cut variants (E_2 × C_1: 33.1, E_2 × C_2: 30.7) compared to the no-cutting variant (E_2 × NC: 40.9), which did not differ significantly from the E_1 variants.

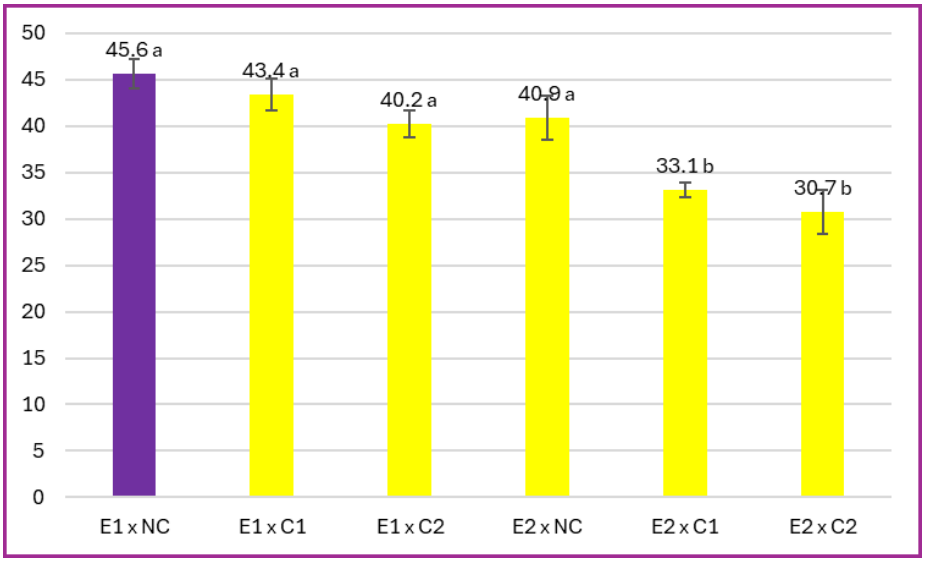

Fig. 4. Chlorophyll content index (CCI) values in hemp as influenced by the interaction between sowing time and cutting type

The results presented in Table 3, referring to the analyzed quality parameters (vitamin C content, TSS, TA, and pH), indicate that sowing time had no significant effect, with the differences being statistically non-significant.

In contrast, cutting type had a significant effect on TSS and TA, while vitamin C content and pH were not statistically influenced. The highest TSS values were recorded in the no-cutting variant and in the variant subjected to two cuts, both showing significant differences compared to C_1, which recorded the lowest values. Regarding TA, the NC variant showed the highest values, followed by C_1, while C_2 exhibited significantly lower values.

Vitamin C content showed slight variation among the variants (64.3 - 65.9 mg/100 g fresh product), with no significant differences. Similarly, pH values remained relatively constant (6.8 - 6.9), indicating that neither sowing time nor cutting type had an effect on this parameter.

Table 3

Effect of sowing time and cutting type on quality parameters in hemp

Variant	Vitamin C (mg/100 g fresh product)	TSS (°Brix)	TA (meq/100 g fresh product)	pH
Sowing time				
E_1	64.5 ± 0.8	9.9 ± 0.4	4.1 ± 0.4	6.9 ± 0.0
E_2	65.9 ± 0.4	10.5 ± 0.1	3.5 ± 0.4	6.9 ± 0.0
Significance	*ns*	*ns*	*ns*	*ns*
Cutting type				
NC	64.3 ± 1.4	11.3 ± 0.3 a	4.7 ± 0.8 a	6.8 ± 0.0
C_1	65.9 ± 0.5	9.0 ± 0.4 b	4.0 ± 0.3 a	6.9 ± 0.0
C_2	65.5 ± 0.3	10.3 ± 0.3 a	2.7 ± 0.2 b	6.9 ± 0.0
Significance	*ns*	*	*	*ns*

E_1 - epoch I, E_2 - epoch II; NC - no-cutting, C_1 - one cut, C_2 - two cuts; TSS - total soluble solids; TA - titratable acidity; Values are presented as mean ± standard error (SE). Within each column, ns - no statistically significant difference, * - statistically significant difference, values associated to different letters are significantly different according to Duncan's test at $p<0.05$.

Overall, the results suggest that cutting type has a more pronounced influence than sowing time on certain quality parameters, particularly TSS and TA, while the other parameters showed little variation.

The analysis of the interaction between sowing time and cutting type revealed significant effects on vitamin C content, total soluble solids, and titratable acidity, while pH was not significantly affected, indicating a relative stability of this parameter in relation to the studied factors, as shown in Table 4.

Table 4

Effect of the interaction between sowing time and cutting type on quality parameters in hemp

Variant	Vitamin C (mg/100 g fresh product)	TSS (°Brix)	TA (meq/100 g fresh product)	pH
E_1 x NC	62.9 ± 2.1 b	10.8 ± 0.3 ab	5.5 ± 1.0 a	6.8 ± 0.1
E_1 x C_1	65.3 ± 0.3 ab	8.5 ± 0.7 c	4.3 ± 0.1 ab	6.9 ± 0.0
E_1 x C_2	65.2 ± 0.1 ab	10.4 ± 0.2 b	2.6 ± 0.2 b	6.9 ± 0.1
E_2 x NC	65.6 ± 0.9 ab	11.8 ± 0.5 a	4.0 ± 0.8 ab	6.8 ± 0.0
E_2 x C_1	66.4 ± 0.7 a	9.5 ± 0.0 bc	3.6 ± 0.7 ab	6.9 ± 0.0
E_2 x C_2	65.8 ± 0.4 ab	10.2 ± 0.4 b	2.8 ± 0.2 b	6.9 ± 0.0
Significance	*	*	*	*ns*

E_1 - epoch I, E_2 - epoch II, NC - no-cutting, C_1 - one cut, C_2 - two cuts; TSS - total soluble solids; TA - titratable acidity; Values are presented as mean ± standard error (SE). Within each column, ns - no statistically significant difference, * - statistically significant difference, values associated to different letters are significantly different according to Duncan's test at $p<0.05$.

Vitamin C content varied within a relatively narrow range, with values between 62.9 and 66.4 mg/100 g fresh product. The highest value was recorded in the $E_2 \times C_1$ variant, being significantly higher than $E_1 \times$ NC, but not significantly different from the other experimental variants. In general, the application of cutting resulted in a slight increase in vitamin C content, more evident under the E_2 sowing time.

Regarding total soluble solids, values ranged between 8.5 and 11.8 °Brix, with the highest values recorded in the $E_2 \times$ NC variant (11.8 °Brix), which was significantly higher than most of the other variants. The application of cutting generally led to a reduction in TSS values, more pronounced in the case of a one cut (C_1).

Titratable acidity was significantly influenced by the interaction between factors, with values ranging from 2.6 to 5.5 meq/100 g fresh product. The highest TA was recorded in $E_1 \times$ NC, while the C_2 variants showed the lowest values, indicating a decreasing trend with an increasing number of cuts.

In contrast, pH was not significantly affected, with values remaining relatively constant (6.8 - 6.9), suggesting that variations in TA were not sufficient to induce relevant changes in the medium reaction.

The interaction between sowing time and cutting type indicates that these quality parameters are influenced by the applied technological practices.

CONCLUSIONS

The results showed that cutting type had a more pronounced influence than sowing time on yield components, particularly on fresh and dry inflorescences yield, highlighting its importance as a technological factor.

Sowing at the first epoch generally resulted in higher yield values compared to the second epoch, although its effect was statistically significant only for dry inflorescences.

Regarding quality characteristics, the sowing time did not significantly influence the analyzed values, whereas the cutting type led to variations in TSS and titratable acidity, highlighting a more pronounced effect of cutting on the evaluated parameters.

The significant interaction between the studied factors highlights the importance of correlating technological practices, namely the cutting type with sowing time, in order to optimize the productive and qualitative potential.

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RESEARCH ON THE EVOLUTION OF WATER QUALITY PARAMETERS IN FISH PONDS DURING THE COLD SEASON IN THE CONTEXT OF CLIMATE CHANGE

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CERCETĂRI PRIVIND EVOLUȚIA PARAMETRILOR DE CALITATE AI APEI ÎN BAZINELE PISCICOLE ÎN SEZONUL RECE, ÎN CONTEXTUL SCHIMBĂRILOR CLIMATICE

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ABSTRACT

The research presents scientific data and information resulting from monitoring the most important water quality parameters in the pond during the cold season (November 2024 – March 2025), in order to assess the impact of climate change on aquatic ecosystems used for fish farming. The analysis focused on physical parameters (water temperature and turbidity) and chemical parameters (dissolved oxygen, salinity, pH, and nitrogen compounds), tracking variations specific to periods of low temperatures and their influence on fish wintering conditions. The results obtained highlight the major role of climate fluctuations in altering the ecological balance of fish ponds and emphasize the need to apply monitoring and adaptive management measures to maintain the productivity and sustainability of fish farming systems. The water temperature had average values between 3.35 and 10.65°, and turbidity fluctuated, with some occasional increases, but in general the values remained low. The values of the chemical parameters monitored showed relative stability of pH and high levels of dissolved oxygen (≈9–10 mg/L), nitrites (NO_2^-) and nitrates (NO_3^-) had low values, with no risk of toxicity, but ammonium (NH_4^+) showed moderate variations between ponds, indicating effective management of mineralization processes. The warming trend in water temperature is a major challenge for the sustainability of aquaculture.

REZUMAT

Cercetarea prezintă datele si informațiile științifice rezultate ca urmare a monitorizării celor mai importanți parametrii de calitate ai apei în helește pe durata sezonului rece (noiembrie 2024 – martie 2025), pentru evaluarea impactului schimbărilor climatice asupra ecosistemelor acvatice utilizate în scop piscicol. Analiza a vizat parametrii fizici (temperatura și turbiditatea apei) și chimici (oxigenul dizolvat, salinitatea, pH-ul și compușii azotului), urmărindu-se variațiile specifice perioadelor cu temperaturi scăzute și influența acestora asupra condițiilor de iernare a peștilor. Rezultatele obținute evidențiază rolul major al fluctuațiilor climatice în modificarea echilibrului ecologic al bazinelor piscicole și subliniază necesitatea aplicării unor măsuri de monitorizare și management adaptativ, pentru menținerea productivității și sustenabilității sistemelor piscicole.Temperatura apei a avut valori medii cuprinse între 3,35 și 10,65°, iar turbiditatea a prezentat fluctuații, cu unele creșteri punctuale, dar în general valorile au rămas reduse. Valorile parametrilor chimici urmăriți au evidențiat o stabilitate relativă a pH-ului și niveluri ridicate ale oxigenului dizolvat (≈9–10 mg/L), nitriții (NO_2^-) și nitrații (NO_3^-) au avut valori scăzute, fără risc de toxicitate, dar amoniul (NH_4^+) a prezentat variații moderate între helește, indicând o gestionare eficientă a proceselor de mineralizare. Tendința de încălzire asupra regimului termic al apei constituie o provocare majoră pentru sustenabilitatea acvaculturii.

INTRODUCTION

Climate change is one of the greatest current challenges for aquatic ecosystems, directly influencing the ecological balance and productivity of fish farming systems. In recent years, temperature changes, precipitation variations, and extreme phenomena associated with the cold season have put additional pressure on fish ponds, affecting water quality and, implicitly, fish health *(D'Abramo and Slater, 2019; Choi et*

al., 2021). Water chemistry is influenced by precipitation at several levels, altering the balance of key physical and chemical indicators of water, nutrient loading, and gas exchange.

Aquaculture is directly dependent on the quality of the physical and chemical parameters of the water sources supplying fish ponds, among which water temperature plays an essential role, influencing fish metabolism, dissolved oxygen solubility, and the dynamics of chemical compounds in water *(Vagner et al., 2019; Li et al., 2022)*. In our country, the temperature range of aquatic ecosystems falls within relatively narrow limits (-30°C, +40°C), resulting in water temperatures between +2°C and +30°C *(Usatîi et al., 2021; Wong & Candolin, 2015; Menon et al., 2023)*.

Under the specific climatic conditions in Romania, the average water temperature in fish ponds during winter generally ranges between 2 and 5°C. During the cold season, the metabolic activity of fish decreases significantly, to a state of deep physiological rest, equivalent to hibernation. An increase in water temperature reactivates metabolic processes, which seriously disrupts the biological cycle of fish, affecting their metabolism and reproductive cycle, especially in species that synchronize their reproduction with seasonal temperatures *(Ferreira et al., 2011; Volkoff and Rønnestad, 2020; Islam et al., 2022)*. Water quality is the key factor in biological processes in fish ponds, and monitoring physical and chemical parameters is essential for maintaining a stable aquatic environment *(Abdullah et al., 2025).*

During the cold season, lower temperatures and reduced photosynthetic processes can lead to a decrease in dissolved oxygen concentration, while the accumulation of nitrogen compounds can significantly affect fish metabolism *(Teal et al., 2008; Galappaththi et al., 2020; Alfonso et al., 2021).* Variations in pH, salinity, and turbidity can also influence biochemical processes and the trophic balance of the ecosystem. Precipitation can increase turbidity through soil erosion and suspended particles, reducing light penetration and photosynthesis. High turbidity can block fish gills and reduce primary productivity. In terms of water quality, for example, uneven temperature gradients profoundly influence fish behavior and shape their complex adaptations and responses aimed at optimizing survival strategies *(Fu et al., 2018; Nadermann et al., 2019; Olesen et al., 2019).*

In this context, the present study aims to analyze the evolution of the most important water quality parameters in fish ponds during the cold season, with a focus on the relationship between climatic factors and the stability of the aquatic environment. The results obtained provide a scientific basis for the adoption of adaptive management measures aimed at ensuring the sustainability and productivity of aquaculture systems in the context of climate change.

MATERIALS AND METHODS

The study was conducted in fish ponds belonging to the Nucet Fish Farming Research and Development Station (SCDP Nucet), which covers an area of 167 ha of water surface, divided into approximately 90 ponds of different sizes and uses. Monitoring was carried out during the cold season, i.e. from November 2024 to the end of February 2025, with the aim of analyzing the most important water quality parameters in order to assess the impact of climate change on the aquatic environment and the health of fish.

The ponds studied are located along the main channel of the Ilfov stream, downstream from the Ilfoveni reservoir (Fig.1). Water is supplied by gravity from this stream, and the water used in aquaculture systems is discharged back into the same channel. During the wintering period, a minimum maintenance flow of 2–4 l/sec/ha was maintained to ensure adequate oxygenation and temperature conditions.

Fig. 1 - Description of the site – SCDP Nucet
(source: https://earth.google.com)

The fish stock was harvested between November 10 and 15, 2024, and introduced for wintering in accordance with technological standards, in ponds of different sizes and depths, depending on their age and size. The depth of the wintering ponds ranges from 1.5 to 2.4 m.

The monitored parameters were divided into two categories:

- Physical parameters: water temperature and turbidity;
- Chemical parameters: dissolved oxygen, salinity, pH, and nitrogen compounds (ammonium, nitrites, nitrates).

Water samples were collected at the beginning and middle of each month in inert, high-density polyethylene (HDPE) containers from 20 points, that is 19 ponds and the water supply source, the Ilfov stream (Figure 2). A total of 200 water samples were collected between November 2024 and March 2025 and analyzed for quality parameters. The air temperature was monitored daily, three times a day (at 8:00 a.m., 12:00 p.m., and 4:00 p.m.), at the local weather station located within the SCDP-Nucet perimeter.

Fig. 2 - Overview of the experimental basins studied
(Source: https://earth.google.com)

In accordance with the recorded air temperature values, the temperature of the ponds was determined at the same times, as well as the dissolved oxygen content, which must be maintained at a minimum level of 5-6 mg/l.

The water temperature, dissolved oxygen, and saturation were determined using a portable Hanna Instruments HI9829-11042 multiparameter meter (Hanna Ltd., Romania) equipped with GPS, and a

turbidimeter was used to determine turbidity. The pH was determined using a portable Dostmann KLH9 pH meter (1.0-14 pH). The concentration of nitrogen anion, nitrite anion, and ammoniacal nitrogen were determined in the laboratory using the spectrophotometric method (Griess-Ilosvay method). Alkalinity was determined in the laboratory using the volumetric method.

The collected data were statistically processed using descriptive and comparative analyses to highlight trends and variations in parameters in relation to the climatic conditions specific to the cold season. The results were presented in tables and graphs, facilitating the interpretation of the impact of climatic fluctuations on water quality and fisheries management.

RESULTS

200 water samples were collected from 20 artificial ponds at the Research and Development Institute for Fish Farming in Nucet (i.e., 40 samples/pond, twice/month at the beginning and middle of each month during the cold season, from November 2024 to March 2025) and analyzed for water quality indicators. The results were interpreted in accordance with the provisions of the "Standard for the classification of surface water quality," correlated with data from the specialized literature in the field of water used for fish farming (OMMGA No. 161/2006). Water and air temperature values between November 2024 and March 2025 showed significant variations, with trends that can be correlated with seasonal climate change (Table 1).

Table 1

Average water and air temperatures between November 2024 and March 2025

MONTH	YEAR	Water temperature °C				Air temperature °C			
		Minimum	Maximum	Average	Standard deviation	Minimum	Maximum	Average	Standard deviation
November	2024	4.4	14.1	7.03	±2.37	-2.0	20.0	6.41	± 3.51
December	2024	3.0	7.0	5.24	±1.05	-2.0	15.0	4.51	± 2.34
January	2025	2.5	6.5	4.55	±1.15	-6.5	17.2	5.59	±3.52
February	2025	1.5	6.5	3.35	±1.59	-10.0	12.0	0.44	±3.77
March	2025	4.5	14.8	10.65	±2.74	0	23.5	11.20	±4.12

Thus, in December (2024) and February (2025), the average water temperature ranged between 3.35°C and 5.24°C, respectively, corresponding to the cold season. However, it should be noted that in January 2025, the average air temperature (5.59°C) was higher than in December (4.51°C), suggesting an atypically warmer period in the middle of winter.

In March 2025, the average water and air temperatures were higher than expected for the end of the cold season, indicating early warming that influenced the biological cycle of fish species. The increase in temperatures during the transition months (November and March) signals a shortening of the cold season and a possible shift in the development and reproduction stages of fish species (Fig. 3).

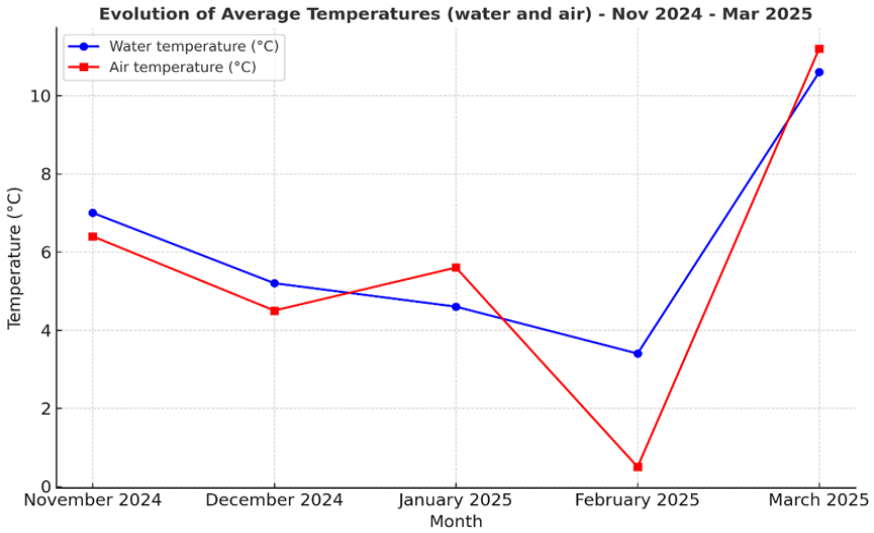

Fig. 3 - Evolution of average temperatures during the cold season (November 2024–March 2025)

Although December and February showed normal characteristics for the cold season, the values recorded in January and March highlight the warming trend and change in climate patterns, with possible implications for the ecological balance of the pond.

The analysis of the chemical parameters of the water in the studied ponds showed overall stability, with some differences between basins. The average values and standard deviations for the parameters monitored showed moderate variations in water quality during the period analyzed. The parameters analyzed were: turbidity, pH, dissolved oxygen (DO), nitrites (NO_2^-), nitrates (NO_3^-), ammonium (NH_4^+), and alkalinity (Table 2).

Table 2

Average values of the main parameters of pond water during the cold season

Parameters	MU	Average/ ± STDEV
pH	pH units	7.00 ± 0.30
Dissolved oxygen (DO)	mg/L	9.90 ± 0.90
Nitrites (NO_2^-)	mg/L	0.04 ± 0.01
Nitrates (NO_3^-)	mg/L	0.05 ± 0.02
Ammonia (NH_4^+)	mg/L	0.55 ± 0.15
Turbidity	FNU	5.5 ± 3.0
Alkalinity	mg/L HCl 0,1N	2.70 ± 0.50

Analysis of the data shows the following:

- The pH remained stable around neutral (≈7), indicating water suitable for maintaining biological balance.
- Dissolved oxygen (DO) had high values (≈9–10 mg/L), suggesting good oxygenation of the experimental basins, which is essential for aquatic organisms.
- Nitrate and nitrite concentrations were low, confirming a low load of nitrogen compounds and a low risk of nitrate pollution.
- Ammonium (NH_4^+) levels varied moderately but remained within acceptable limits for aquatic environments, indicating effective management of mineralization processes.
- Moderate alkalinity reflects adequate buffering capacity, preventing sudden pH variations.
- Turbidity fluctuated, with some occasional increases, but values remained low overall, suggesting clear water with little suspended particulate matter (Table 3).

The variation in the chemical parameters of the monitored ponds during the cold season (November 2024-March 2025) is shown in Table 3, and the variation in the average values of the chemical parameters of the water is shown in Fig. 4.

Table 3

Summary of values for the main water parameters in the analyzed ponds

Parameters	Value range (ponds)	General remarks
pH	6.94 – 7.19	Almost neutral, optimal for most fish species
Alkalinity (mg/L)	2.52 – 2.82	Moderate level, acting as a pH buffer.
Dissolved oxygen (mg/L)	9.48 – 10.28	High and stable value, favorable for fish respiration.
Nitrites (mg/L)	0.03 – 0.07	Low value, no toxic risk.
Nitrates (mg/L)	0.04 – 0.08	Low value, characteristic of waters with controlled nutrient input.
Ammonia (mg/L)	0.36 – 0.79	In some ponds, it exceeds 0.7 mg/L → organic load.
Turbidity (FNU)	3.09 – 13.20	Large variations between basins, some waters more turbid.

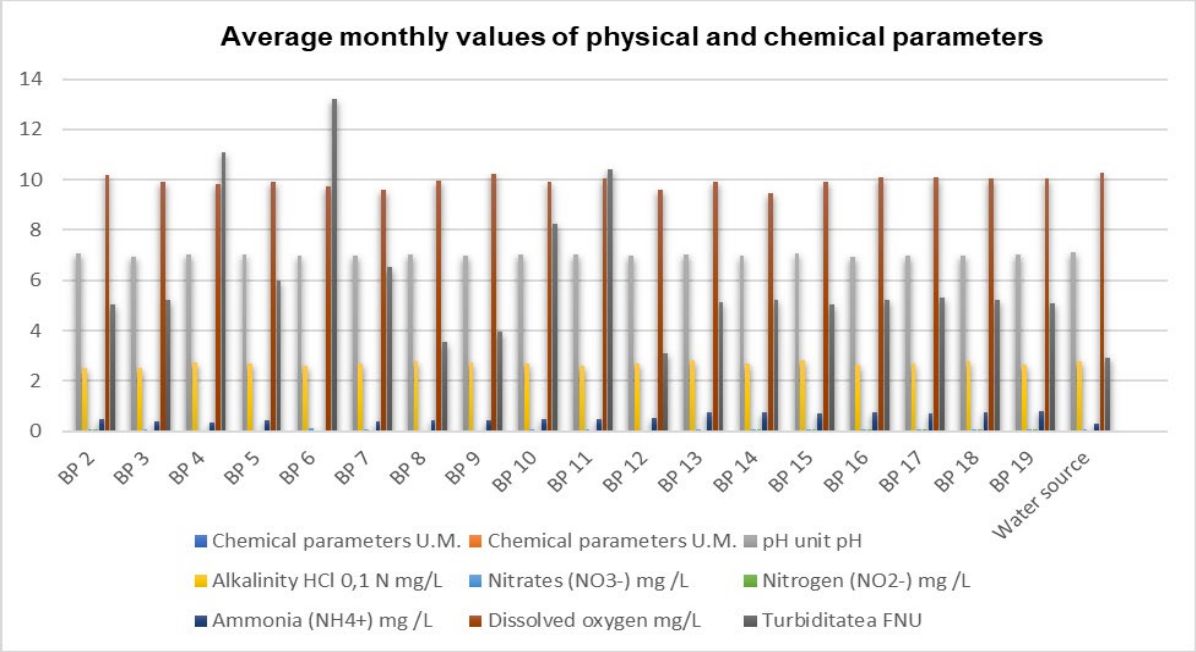

Fig. 4 - Comparison of minimum and maximum values for water quality parameters (November 2024 - March 2025)

From the analysis of the average values of the main chemical parameters of the monitored ponds, the following results were obtained:

- The pH recorded values close to neutral (6.9–7.1), which is an optimal level for most fish species, avoiding both acidification and excessive alkalization.
- Alkalinity remained at moderate values (~2.5–2.8 mg/L), which contributes to good water buffering and prevents sudden pH variations.
- Dissolved oxygen was within high limits (9.5–10.3 mg/L), indicating good oxygenation, favorable for fish metabolism and nitrification processes.
- Nitrites and nitrates were very low, indicating efficient oxidation processes and a lack of significant nutrient pollution.
- Ammonia varied between basins; in general, the values are acceptable, but some exceed the threshold of 0.7 mg/L, which can affect the sensitivity of fish species and indicates an accumulation of organic matter.
- Turbidity varied considerably between ponds (3–13 FNU). More turbid waters can reduce light penetration and, implicitly, phytoplankton productivity, but the values do not exceed critical levels for aquaculture.

Overall, the results indicate that most basins have good water quality for fish growth, but continuous monitoring of ammonium and turbidity is essential to prevent imbalances.

CONCLUSIONS

The analysis of the physical and chemical parameters of the water in fish ponds, correlated with the air and water temperature regime during the period analyzed, highlights the fact that aquatic ecosystems are directly influenced by climate change and local environmental factors. Temperatures higher than the usual average for the winter months suggest a warming trend that could substantially alter the seasonal cycle of fish species, influencing fundamental processes such as reproduction, growth, and survival. According to recorded data, the winter season or hibernation period of 2024-2025 lasted approximately 130 days.

The relative stability of pH and high levels of dissolved oxygen demonstrate an aquatic environment favorable to metabolism and maintenance of trophic balance, while low, but variable concentrations of nitrogen compounds and fluctuating turbidity reflect complex processes of mineralization and circulation of organic matter, with potential effects on primary productivity. The alkalinity and buffering capacity of the water support the system's resistance to sudden pH variations, which is an essential factor for ecosystem stability.

The results indicate that the monitored parameters remain within the general safety limits for fish growth, but the effects of the warming trend on the water temperature regime pose a major challenge to the sustainability of aquaculture.

Monitoring essential water parameters, including temperature, dissolved oxygen (DO), pH, ammonia (NH_3), nitrites (NO_2^-), and turbidity, is vital to ensuring optimal habitat conditions. Low temperatures reduce fish metabolic rates and food intake, while the risk of oxygen depletion under ice cover increases, potentially leading to hypoxic stress and winter mortality. In addition, the accumulation of toxic compounds such as ammonia and nitrites can occur due to limited biological filtration during winter. The implementation of fundamental management strategies, such as aeration systems and ice management techniques, can reduce risks during winter. This study highlights the importance of accurate monitoring of pond water quality during fish species overwintering to minimize mortality and ensure species resilience under challenging environmental conditions.

Therefore, the data obtained highlights the need for integrated fisheries management that takes into account both current environmental conditions and climate trends in order to ensure the long-term viability and productivity of fish farms.

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DIGITAL AGRICULTURE - USE OF ARTIFICIAL INTELLIGENCE IN AGRICULTURAL PRODUCTION / *AGRICULTURA DIGITALĂ - UTILIZAREA INTELIGENȚEI ARTIFICIALE ÎN PRODUCȚIA AGRICOLĂ*

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ABSTRACT

Digital agriculture integrates artificial intelligence to analyze complex field data (satellite images, sensors, drones), providing farmers with fast and accurate decisions. Through artificial intelligence - AI, sowing, fertilization and irrigation processes can be optimized, which leads to increased productivity and reduced resource consumption. Predictive models based on AI help anticipate diseases and pests, reducing the risk of losses and dependence on pesticides. The implementation of artificial intelligence in agriculture transforms production into a sustainable, competitive and adapted system to current climatic and economic challenges.

REZUMAT

Agricultura digitală integrează inteligența artificială pentru a analiza date complexe din câmp (imagini satelitare, senzori, drone), oferind fermierilor decizii rapide și precise. Prin inteligenta artificiala- IA, se pot optimiza procesele de semănat, fertilizare și irigare, ceea ce duce la creșterea productivității și reducerea consumului de resurse. Modelele predictive bazate pe IA ajută la anticiparea bolilor și dăunătorilor, reducând riscul pierderilor și dependența de pesticide. Implementarea inteligenței artificiale în agricultură transformă producția într-un sistem sustenabil, competitiv și adaptat provocărilor climatice și economice actuale

INTRODUCTION

Agriculture is undergoing rapid transformation, driven by global challenges such as climate change, population growth and pressure on natural resources. According to a report by the Food and Agriculture Organization (FAO), the world population will reach 9.7 billion by 2050, which will require a significant increase in agricultural production to meet food demands. In this context, traditional agriculture is no longer sufficient to meet these challenges, and digitalization is becoming a necessity, (*Aijaz, N.,2025*).

Digital agriculture is the integration of digital technologies into agricultural processes, with the aim of improving efficiency, sustainability and productivity. It includes the use of sensors, drones, satellites and software platforms to collect and analyze data, thus facilitating informed decision-making. According to a study published, the integration of artificial intelligence in agriculture has demonstrated significant improvements in crop management and resource optimization.

The world's population is gradually increasing, and statistics predict an increase of up to 10 billion inhabitants by 2050. In this context, agricultural production must be improved by up to 70% to ensure the food needs of the planet's inhabitants, while taking into account climate change and the importance of using more sustainable methods, with reduced energy, pesticide and fertilizer consumption. To meet these requirements, agriculture has evolved into what we today call Agriculture 4.0. Agriculture 4.0 will be green, based on the use of technology, with the aim of responding to the real needs of farmers and consumers. Techniques such as robots, temperature and humidity sensors or GPS will transform agriculture into an efficient, profitable and sustainable one. These technologies can influence agriculture by, (*Abbas, et al. 2023*). Innovation of agricultural production techniques, Use of diverse technologies to streamline agri-food chains, Incorporation of multifunctional technologies.

E-Agriculture involves the design, development and application of innovative ways of using information and communication technologies (ICT), with a primary focus on agriculture. The aim is to stimulate the development of agriculture and rural areas by improving access to valuable information that can help agricultural actors make the best possible decisions and use available resources in the most productive and sustainable way. Technologies that can be harnessed for e-agriculture can include devices, networks,

services and applications. These can range from cutting-edge internet-based technologies and sensing tools to other technologies that have been around for a long time, such as radio, landlines, televisions, mobile phones and satellites. In an increasingly knowledge-intensive sector, access to the right information, at the right time, in the right format and through the right channel can make a crucial difference to the livelihoods of stakeholders involved in agriculture and related fields (*FAO, 2017*).

Among the most common technologies used in the agriculture of the future is Artificial Intelligence. This technology has revolutionized the world and has an untapped potential in the agricultural field. However, statistics show that agriculture is one of the segments in which technology can excel due to the multitude of applications in which it can be used, as well as the benefits brought: **Cost reduction.** Artificial intelligence can be used in sustainable agriculture to analyze the quality of soil and crops, making an important contribution to identifying areas that need treatments, fertilization or irrigation. In this way, the technology recommends best practices to maximize harvests and reduce expenses. **Process automation.** The lack of labor can be avoided by implementing intelligent solutions. Artificial Intelligence brings with it a series of automations that can be used to process land, with reduced human involvement. Compared to the work resulting from human involvement, intelligent solutions are more efficient and more precise, reducing the risks caused by individual mistakes, (*Avila F. ,2025*). **Decision support.** Artificial intelligence can help monitor and analyze various soil indicators, as well as the entire agri-food chain. In this way, farmers can obtain valuable information about the crop, soil and market demand, to determine the optimal crop types and the right times for sowing and harvesting.

IoT, or the Internet of Things, is a complementary technology to Artificial Intelligence, which allows farmers to improve their productivity, by using sensors that measure external factors such as: light; humidity levels in the air and soil; precipitation levels; temperature. In this way, farmers can monitor the entire crop intelligently and can perform certain operations such as irrigation, even remotely. The Internet of Things has the potential to revolutionize agriculture through: **Smart greenhouses**: developed with Internet of Things technology, they can completely eliminate human involvement by monitoring and controlling the environment conducive to crop development **Farm monitoring**: there are various applications through which farmers can collect data not only on the crop, but also on the condition and health of animals, thus avoiding the spread of certain diseases. **Agricultural drones**: These devices can be used for crop analysis, irrigation, soil analysis, or even planting. **Smart sensors:** The use of devices such as motion detectors, control systems, or autonomous vehicles can help manage farms efficiently and monitor their performance.

MATERIAL AND METHOD

The Romanian economy relies to a much higher extent on agriculture compared to other European countries. For comparison, according to the latest data provided by the World Bank, in 2021 agriculture, forestry and pisciculture contributed approximately 4.3% to the formation of the Gross Domestic Product in Romania, while the average of European countries was 3 times lower, standing at approximately 1.6% (https://data.worldbank.org). From a GDP/capita perspective, in 2020 Romania is far behind the EU27 average. The growth trend is encouraging, which is faster in Romania compared to other countries in the area (Hungary, Slovakia or Bulgaria) (Figure 1). The agricultural area used in Romania is about 13.3 million ha (55.9%), of which approximately 8.3 million ha is represented by arable land, given that the territory of Romania totals 23.8 million ha. The ratio between the country's arable area and the number of inhabitants shows that each inhabitant of Romania has on average about 0.41 ha of arable land, a value higher than many countries in the European Union and almost double the EU 27 average, which is 0.212 ha/inhabitant (*Source: https://www.madr.ro/docs/agricultura/agricultura-romaniei-2015.pdf*).

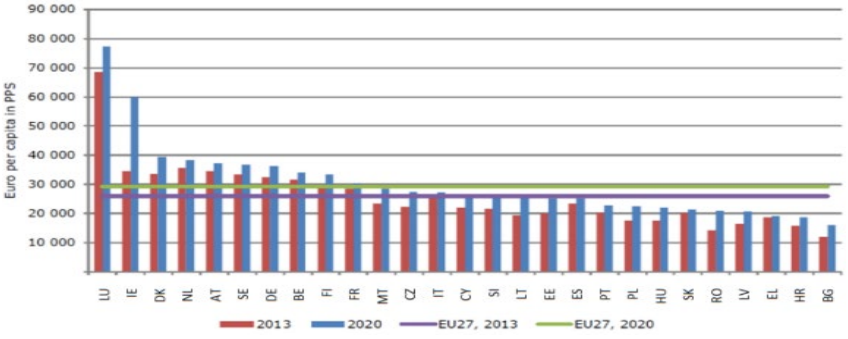

Fig. 1. Evolution of GDP per capita compared to Romania and EU member states

(Source: European Commission (2021). Statistical factsheet European Union)

From the perspective of land use categories, Romania has a distribution similar to the European average between arable land and pastures and hayfields. This last category of land use has an important share (approximately 30% of total agricultural land) being mainly located in hilly and mountainous areas with major implications on agri-environmental conditions. The area dedicated to permanent crops is below the European average (Figure 2).

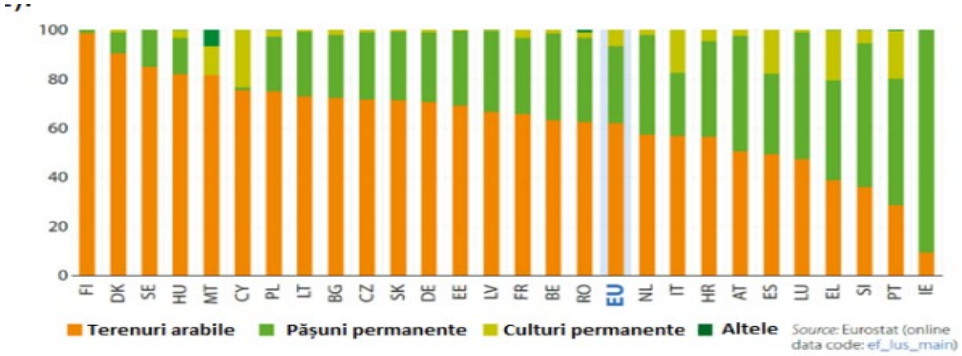

Fig. 2. Distribution of agricultural land according to various categories of use compared Romania/EU member states (% in 2016) (https://ec.europa.eu/eurostat/web/products-statistical-books/-/ks-fk-21-001)

In 2020, agriculture, forestry and pisciculture had a 3 times higher contribution to the formation of GDP compared to the European average. These sectors are of major importance in the Romanian economy;
Arable land resources in Romania are twice as important as the European average;
Approximately 30% of the utilized agricultural area is represented by permanent meadows and pastures generally located in the mountainous area and having particularities in terms of the way of exploitation – smaller farms; the link between agriculture and biodiversity; more difficult access; The model based on the traditional semi-subsistence family farm is increasingly less important in the total utilized agricultural areas (under 2 Ha). Large farms of over 100 hectares, although representing a very small number in total, exploit around 50% of the total land resources. The medium-sized farms on which the European agricultural model is based, located between 20 and 100 hectares, have a small share both in the total agricultural area used and in the number of farms.

According to the latest evaluations of the Digital Economy and Society Index, Romania ranks last in the European Union (Fig.3). This index is developed at the level of the entire economy. Agricultural sectoral statistical data are less accessible as they are not collected in official national or European statistics. Consequently, the main components of the DESI index were completed by Romanian and European statistical data available within the analyzed chapters, namely: human capital; connectivity; integration of digital technologies; and digital public services, (European Commission) :

	România		UE
	loc	punctaj	punctaj
DESI 2022	27	30,6	52,3

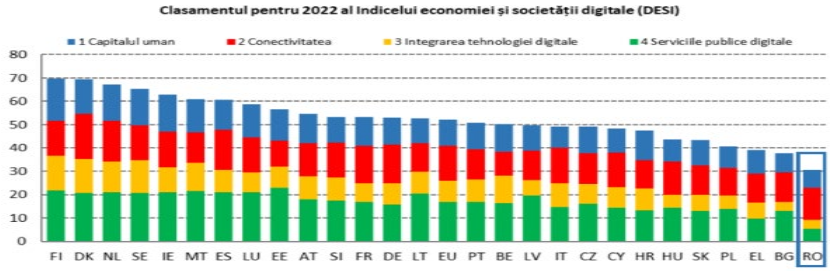

Fig.3. 2022 Digital Economy and Society Index Ranking
(European Commission, 2022. Digital Economy and Society Index – Romania)

Starting from the above, for the implementation of digital agriculture and artificial intelligence in agricultural production, a complex methodology is required that integrates multiple data sources, technological tools and information processing techniques. The main objective is to transform data collected

from the field into practical recommendations for farmers and decision-makers. Within this approach, the methods are selected in such a way as to ensure the accuracy, reliability and applicability of the results, (*Babar A.,2024*).

Data collection. Data collection is the first essential step in digital agriculture. Data comes from a variety of sources, including: IoT (Internet of Things) sensors: Placed in the soil, on crops or in irrigation systems, they monitor parameters such as soil moisture, temperature, nutrient levels or pH in real time. This data allows farmers to optimize irrigation and fertilizer application, reducing waste and costs. Drones and aerial imaging: Drones equipped with multispectral or thermal cameras provide detailed images of crops, allowing the detection of water stress, pest attacks or areas affected by diseases. The analysis of these images is essential for making quick and accurate decisions. Satellite data and remote sensing: These provide large-scale information on the state of vegetation, crop evolution and climate conditions. The use of images from satellites such as Sentinel-2 or Landsat allows for continuous monitoring and strategic planning of interventions. Historical and statistical data: Reports on crop yields, input application history, and past climate conditions are integrated to build robust predictive models.

Data processing and analysis. After data collection, it must be processed and analyzed to be usable in decision-making:Data cleaning and normalization: Raw data is subjected to filtering processes to eliminate errors and outliers. This step is essential to avoid misinterpretations or erroneous decisions. Big data analysis: Large volumes of information are processed using cloud platforms and specialized software, which allow the identification of patterns, correlations and anomalies. Application of artificial intelligence algorithms: Machine learning, deep learning and neural network algorithms are used to build predictive models. These models allow for yield estimation, early detection of diseases and pests, as well as resource optimization. Integration into decision-making platforms: The results of the analyses are transmitted to digital platforms that provide real-time recommendations to farmers, such as the optimal time for irrigation, fertilizer application or phytosanitary treatments.

Artificial Intelligence Models and Techniques. In digital agriculture, different types of AI are applied depending on the purpose and data availability: Machine Learning: Regression, classification and clustering models are used for yield forecasting, pest detection or crop classification. Deep Learning: Convolutional Neural Networks (CNN) are used in the analysis of aerial and satellite images, identifying areas affected by diseases or water stress. Optimization algorithms: These allow minimizing costs and resource consumption by calculating the most efficient irrigation, fertilization and harvesting plans.

Methodological integration and validation. For the applied methods to be relevant and applicable, validation of the results is necessary: Field testing: The developed models are tested in pilot farms to verify the accuracy of the predictions and the efficiency of the recommendations. Comparison with historical data: The predictive models are evaluated by reporting them to real data from previous years, in order to adjust the parameters and increase the accuracy. Continuous feedback: Farmers provide information on the implementation of the recommendations, and the models are recalibrated periodically,(*FAO. 2025*).

RESULTS

Agricultural Robots: The Future of Field Workers. Devices that combine both Artificial Intelligence and the Internet of Things are agricultural robots, used by more and more farmers globally. They are equipped with specific systems that allow multiple operations to be carried out, such as: Autonomous machinery and vehicles**,** this type of robots can operate non-stop, thus streamlining processes and reducing labor costs. Autonomous tractors and machinery can perform various operations, from plowing to sowing or harvesting, based on navigation systems based on GPS technology. Animal monitoring **-** in the field of animal husbandry, robots can be used to monitor the health of animals or to feed them. There are robots that can perform specific operations such as milking cows, based on concrete data, to ensure that they provide constant milk production. Precision farming In this case, robots are equipped with sensors and cameras to monitor precision crops, collecting important data. They can also be equipped with devices for weeding, harvesting or planting crops, reducing the need for human involvement., (*Kamilaris, A., Kartakoullis, A., & Prenafeta-Boldú, F. X., 2017*).

Data collected through IoT sensors, drones, and satellite imagery allows for precise monitoring of soil moisture, nutrient levels, temperature, and other environmental factors. By analyzing this data with machine learning algorithms, farmers can apply the exact amount of water and fertilizer needed, avoiding waste and unnecessary consumption. Recent studies show that farms that implement AI-based smart irrigation systems can reduce water consumption by up to 25–30%, without affecting crop yields. This has a direct impact on

the sustainability and economic competitiveness of farms, (*Liakos, K. G., Busato, P., Moshou, D., Pearson, S., & Bochtis, D., 2018*).

The integration of AI in agriculture also leads to improved crop productivity and quality. Predictive models allow for yield estimates and early identification of areas with potential stress or pest attack. Thus, interventions can be carried out before losses become significant. For example, disease detection applications using multispectral image analysis can identify outbreaks of infection even before visible symptoms appear, reducing the need for excessive pesticide application. By constantly monitoring and optimizing processes, farms obtain high-quality products with high uniformity and compliance with European standards.

In addition to the use of technology, an important role in the future of agriculture is played by urban agriculture, which is necessary for adapting to climate change and building green spaces in cities. Technological innovations have facilitated production methods that can be used in urban environments to diversify supply chains and increase consumer access to fresh, local food. To make the space needed to grow crops more efficient, vertical farming has been introduced, which makes it possible to build farms in different spaces. The advantages of vertical farming are diverse, such as: Reduction of the area needed for food production; Utilization of unused or neglected spaces;Provides increased yields with low resource consumption;Allows the cultivation of different foods without taking into account their seasonality,(Nautiyal, M., 2025).

Fig. 4. Robotic arm working in urban agriculture

Digital agriculture significantly contributes to reducing environmental impact. Precise application of inputs and optimization of agricultural work reduces soil, water and air pollution. Also, through strategic planning of irrigation and fertilization, greenhouse gas emissions associated with agricultural processes can be reduced. A study conducted in the Netherlands showed that farms using digital platforms and AI for crop management were able to reduce CO_2 emissions by approximately 15%, while maintaining high yields. Biosensors are a green technology with a significant impact in digital agriculture and in ensuring food security. Since food quality and safety are important elements in the quality of life of individuals, monitoring these aspects is necessary to ensure the well-being of the global population. In this context, biosensors, specific devices, have been introduced to analyze the concentration of certain elements and to transmit information about the biochemical reactions that occur, (Michiel Kallenberg, 2025). In this industry, biosensors have the particular role of detecting the various pathogenic organisms present in food, before it reaches the store shelves.

Fig. 5. Personalized food production with the help of technology

The results obtained by integrating digital agriculture show significant differences compared to traditional methods. In traditional farms, decisions are based on the farmer's experience and empirical observations, which can lead to errors and losses. In contrast, digital systems provide recommendations based on concrete data and predictive models, allowing for optimal planning of agricultural work. Comparative studies indicate an average increase in yield by 15–20% and a reduction in input costs by 10–15% in farms that adopt digital agriculture, (*Müjen K., 2025*).

The implementation of digital agriculture and AI has already been tested in various international contexts: United States: Autonomous farms use robots for sowing, harvesting and monitoring crops, which has led to significant reductions in labor costs and increased efficiency. Netherlands: Smart greenhouses integrated with AI allow for automated control of temperature, humidity and nutrients, ensuring high yields and consistent product quality. Israel: AI-based irrigation systems optimize water consumption in extreme drought conditions, allowing farms to maintain stable production, (*adr.gov.ro/wp-content/uploads/2024/03/*).

CONCLUSIONS

In conclusion, the adoption of digital agriculture and artificial intelligence is an essential pillar for the transformation of the agricultural sector in Romania and globally. This not only optimizes resources and increases productivity, but also contributes to sustainability, competitiveness and food security. Applied research, digital infrastructure and farmer education are critical components of the success of this transformation. Therefore, it is absolutely necessary for public authorities, research institutes and farmers to collaborate to promote and implement digital agriculture on a large scale, thus ensuring the development of an innovative, efficient and sustainable agriculture.

Moreover, the integration of digital agriculture has major implications for public policies and economic strategies. Digital systems allow the collection of standardized and accurate data, which can be used by national authorities for agricultural planning, subsidies, food security monitoring and environmental policies. In this sense, digitalization and the use of AI not only support the activity of farmers, but also contribute to the development of a more transparent, efficient and resilient agricultural economy to global changes.

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MODAL VIBRATION ANALYSIS OF AN AGRICULTURAL DRONE STRUCTURE FOR THE PREVENTION OF RESONANCE PHENOMENA
/
ANALIZA MODALĂ A VIBRAȚIILOR STRUCTURII UNEI DRONE AGRICOLE PENTRU PREVENIREA FENOMENELOR DE REZONANȚĂ

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Keywords: *Modal analysis; UAV structure; Resonance prevention; Vibration fatigue; Material optimization*

ABSTRACT

High-power agricultural multirotor drones are subjected to intense vibrational loads generated by brushless motors and large-diameter propellers. These excitations can lead to resonance phenomena in lightweight structural components, particularly in the motor mounting area, promoting material fatigue and premature structural failure. This study investigates the dynamic behavior of an agricultural drone motor mount and evaluates the influence of material selection on its vibrational response. A finite element modal analysis was performed on a real motor mount geometry using two structural materials: EN-AW 3003 aluminum alloy and S235JR structural steel. Identical geometry, boundary conditions, and FEM discretization were applied to both configurations, enabling a direct comparison of their dynamic behavior. The first five natural frequencies, mode shapes, and modal mass participation factors were determined. The study demonstrates that for high-power agricultural drones, mass reduction achieved through the use of aluminum alone is not sufficient to ensure structural reliability, and dynamic stiffness and resistance to vibration-induced fatigue become essential design criteria. The proposed FEM-based methodology provides an effective tool for optimizing UAV structural components subjected to intense vibrational excitation.

REZUMAT

Dronele agricole multirotor de mare putere sunt supuse unor solicitări vibraționale intense generate de motoarele brushless și de elicele de dimensiuni mari. Aceste excitații pot conduce la apariția fenomenelor de rezonanță în componentele structurale ușoare, în special în zona suporturilor de motor, favorizând oboseala materialului și defectarea prematură a structurii. În acest studiu este analizat comportamentul dinamic al unui suport de motor de dronă agricolă și este evaluată influența materialului asupra răspunsului vibrațional. Analiza modală a fost realizată prin metoda elementelor finite asupra unei geometrii reale de suport, pentru două materiale structurale: aliaj de aluminiu EN-AW 3003 și oțel structural S235JR. Pentru ambele variante au fost utilizate aceeași geometrie, aceleași condiții de frontieră și aceeași discretizare FEM, permițând o comparație directă a comportamentului dinamic. Au fost determinate primele cinci frecvențe proprii, formele modale și participarea maselor. Studiul demonstrează că, în cazul dronelor agricole de mare putere, reducerea masei prin utilizarea aluminiului nu este suficientă pentru asigurarea fiabilității structurale, iar rigiditatea dinamică și rezistența la oboseală vibrațională devin criterii de proiectare esențiale. Metodologia FEM propusă oferă un instrument eficient pentru optimizarea componentelor structurale ale UAV-urilor supuse excitațiilor vibraționale intense.

INTRODUCTION

The rapid development of agricultural drones has led to a significant expansion of their application fields, ranging from crop monitoring and phytosanitary treatments to mapping, payload transport, and technical inspections. The increase in operational performance has been accompanied by intensified mechanical and dynamic loads acting on the load-bearing structures, especially in multirotor drones, where the interaction between motors, propellers, and the structure generates complex vibrational excitations. These vibrations may lead to resonance phenomena, with negative effects on structural integrity, component durability, and onboard system accuracy.

In real operating conditions, vibrations in agricultural drones are mainly generated by the propulsion system, which includes high-speed electric motors, propellers, and mounting elements. Rotor imbalances,

rotational speed variations, manufacturing tolerances, and component wear can produce periodic excitations with frequencies close to the natural frequencies of the structure. Under such conditions, resonance can significantly amplify vibration amplitudes, accelerating the onset of structural fatigue and cracking in load-bearing elements. Recent studies have demonstrated that identifying and controlling these vibrations is an essential requirement for improving the reliability and safety of multirotor drones used in agriculture (*Abdullah Salem et al., 2025; Zou et al., 2025)*.

Modal analysis is one of the most widely used methods for investigating the dynamic behavior of mechanical structures. By determining natural frequencies and mode shapes, this method allows the identification of frequency ranges in which the structure is prone to resonance. When applied to drone structures, modal analysis provides essential information on the interaction between geometry, material, and operational loading conditions. Several studies have shown that lightweight structures made of aluminum alloys or composite materials may exhibit relatively low natural frequencies, located close to the excitation frequencies generated by motors and propellers (*Liu et al., 2022; Andries et al., 2025*).

The current trend in agricultural drone design is oriented toward reducing total mass in order to increase flight autonomy and payload capacity. In this context, aluminum is frequently used for manufacturing arms, motor mounts, and other structural components. However, the use of lightweight materials implies a reduction in structural stiffness, which may lead to lower natural frequencies and increased susceptibility to resonance. Experimental studies on the vibration fatigue of aluminum alloys used in aeronautical applications have shown the occurrence of cracks as a result of repeated cyclic loading, even at moderate amplitude levels (*Teng et al., 2022*).

To mitigate vibration effects, the literature proposes several strategies, including vibration isolation, structural geometry modification, material optimization, and active or passive vibration control. Passive isolation systems based on elastomeric elements or flexible structures have been successfully tested to reduce the transmission of vibrations to sensitive payloads such as sensors or optoelectronic equipment (*Fu et al., 2022; Kang et al., 2024; Shi et al., 2025*). However, these solutions do not eliminate the fundamental problem when the main drone structure enters a resonance regime.

A complementary approach consists in the structural redesign of critical components so that the natural frequencies of the assembly are shifted outside the excitation range of the motors. In this regard, numerical modal analysis based on the finite element method is an extremely effective tool. Through numerical simulations, different design variants, materials, and geometries can be rapidly evaluated without the immediate need for physical prototypes. Recent studies have shown that structural optimization, including generative design and additive manufacturing techniques, can lead to significant improvements in the dynamic behavior of drone frames (*Al-Hadithi et al., 2025; Andries et al., 2025*).

Validation of numerical results through experimental methods is essential to ensure the accuracy of modal analysis. Vibration measurements performed using accelerometers allow the identification of dominant frequencies and their associated amplitudes under real operating conditions. Frequency-domain analysis methods, such as Fast Fourier Transform (FFT) and Power Spectral Density (PSD) evaluation, are commonly used to correlate experimental results with numerical predictions [Staffa et al., 2023; Sui et al., 2025]. Although some studies focus on civil or industrial structures, the principles of modal analysis and resonance identification are directly transferable to UAV structures (*Komarizadehasl et al., 2022*).

In agricultural drones, the impact of vibrations is not limited to structural integrity alone. Vibrations can affect the performance of navigation systems, positioning sensors, and transported payloads. For example, vibrations have been shown to introduce significant errors in measurements acquired by UAV-mounted sensors, influencing the accuracy of collected data (*Hedworth et al., 2022*). Similarly, in sensitive applications such as the transport of products or delicate equipment, vibrations may compromise their functionality (*Oakey et al., 2021)*.

Dynamic models of propulsion systems, which include the interaction between the motor, propeller, and structure, provide a deeper understanding of vibration excitation sources. Studies focused on the dynamic modeling of multirotor propellers have highlighted the importance of imbalances and operational faults in generating periodic vibrations (*Zou et al., 2025*). Integrating these models into the modal analysis of the structure allows a realistic evaluation of resonance risk under real operating conditions.

Recent literature shows a growing interest in advanced signal processing and artificial intelligence methods for early detection of vibration-related problems. For instance, the use of neural networks to identify rotor imbalances represents a promising direction for drone health monitoring [Abdullah Salem et al., 2025].

However, such methods are most effective when supported by appropriate structural design that minimizes susceptibility to resonance already at the design stage.

Despite the significant progress reported in the literature, important gaps still exist regarding the direct correlation between modal analysis, real vibration measurements, and material optimization for agricultural drone structures. Many studies focus either on numerical analysis or isolated experimental tests without fully integrating both approaches into a unified framework. Moreover, direct comparisons between commonly used materials, such as aluminum and steel, in the context of drone motor mounts are still relatively limited.

Considering these aspects, the present article aims to contribute to improving the understanding of the dynamic behavior of agricultural drone structures through an integrated approach that combines numerical modal analysis, experimental vibration measurements, and material optimization. The study focuses on a motor mount initially made of aluminum, designed to reduce mass but which exhibited cracks during operation, indicating the occurrence of resonance phenomena. By replacing the material with steel and reassessing the modal behavior, the objective is to shift the natural frequencies outside the excitation range and reduce vibration amplitudes.

The obtained results have the potential to provide practical guidelines for the design of more robust agricultural drone structures with extended service life and increased reliability. Furthermore, the proposed methodology can be adapted and applied to other UAV types or lightweight structures subjected to intense vibrational loading, contributing to the development of optimized constructive solutions for real-world applications.

MATERIALS AND METHODS

Description of the Analyzed UAV Platform

The study was carried out on a full-scale agricultural multirotor drone developed and built for precision agriculture applications involving the transport of high payloads. The aerial platform consists of a rigid central frame to which several symmetrically arranged arms are radially connected, each arm being equipped with an independent propulsion system. The payload is positioned in the lower central area of the drone, while the propulsion units are mounted at the ends of the arms, generating significant dynamic loads on the structure.

Both a three-dimensional CAD model of the drone and a functional physical prototype were used in this research. The CAD model was employed for numerical simulations, while the manufactured prototype was used to perform experimental vibration measurements, allowing the correlation of numerical results with those obtained under real operating conditions.

Fig. 1 – The developed UAV

Propulsion System and Sources of Vibrational Excitation

Each propulsion unit is equipped with a KDE 5215XF-220 brushless motor (Fig. 2), paired with KDE-CF215-DP counter-rotating propellers with a size of 21.5” × 7.5”. Power is supplied by a 12-cell (12S) Li-Po battery with a maximum voltage of 52.2 V, and the motor is capable of generating a thrust of up to 11,350 g.

Based on the motor speed constant (Kv = 220 rpm/V), the theoretical maximum rotational speed is approximately 11,500 rpm, corresponding to a fundamental rotational frequency of about 190 Hz. In addition,

the blade passing frequency associated with the two-blade propellers is approximately 380 Hz. These frequencies, together with their harmonics, represent the main sources of vibrational excitation acting on the motor mount and on the drone structure.

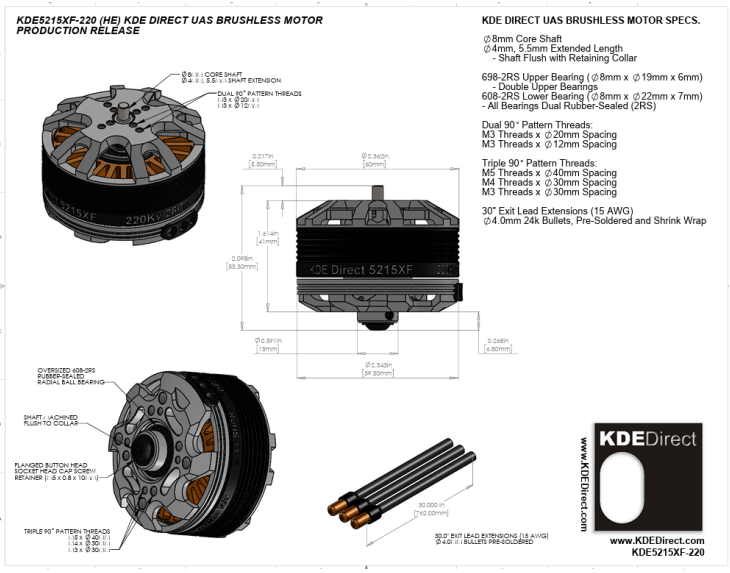


Fig. 2 – KDE 5215XF-220 brushless motor [https://www.kdedirect.com/]

Table 1

Technical Specifications of the KDE 5215XF-220 Moto

Parameter	Value
Motor type	KDE 5215XF-220 brushless motor
Speed constant (Kv)	220 rpm/V
Maximum continuous current*	44+ A (180 s)
Maximum continuous power*	1955+ W (180 s)
Maximum efficiency	> 92%
Operating voltage range	22.2 V (6S) – 50.4 V (12S)
No-load current (Io @ 10 V)	0.6 A
Winding resistance (Rm)	0.080 Ω
Number of stator poles	24 (24S28P, HE)
Number of magnetic poles	28 (24S28P, HE)
Bearings	Triple, 698-2RS / 608-2RS
Mounting pattern	M4 / 3 × 30 mm; M5 × 40 mm
Stator type	5215, 0.2 mm Japanese silicon steel laminations
Shaft diameter	4 mm (8 mm internal)
Shaft length	5.5 mm
Motor diameter	≈ 60 mm
Motor length	41 mm
Motor mass	305 g (360 g with cables)
Maximum propeller size	up to 21.5"-TP (21.5"-DP on 12S)
Motor timing advance	22° – 30°
ESC PWM frequency	16 – 32 kHz (≈ 600 Hz mechanical)

Influence of the ESC PWM Frequency on Vibrational Excitations

An important parameter included in the motor specification table is the PWM modulation frequency of the electronic speed controller (ESC), which lies in the range of 16–32 kHz. Although this frequency is mechanically much higher than the range of interest of the structural modal analysis, it can generate secondary effects on the vibrational behavior of the motor–mount assembly.

From an electromagnetic point of view, the rapid current switching in the motor windings produces pulsating magnetic forces that can induce low-amplitude vibrations at the rotor and stator levels. These excitations are mechanically filtered by the inertia of the system, resulting in an effective vibrational component located in the lower frequency range, estimated at approximately ≈600 Hz from a mechanical standpoint. This value approaches the upper limit of the frequency range analyzed in the present study.

Within the modal analysis, the mechanical frequency associated with PWM effects was therefore considered a secondary excitation, with a lower impact compared to the motor rotational frequency (≈190 Hz) and the blade-passing frequency (≈380 Hz). Nevertheless, the presence of this component is relevant for

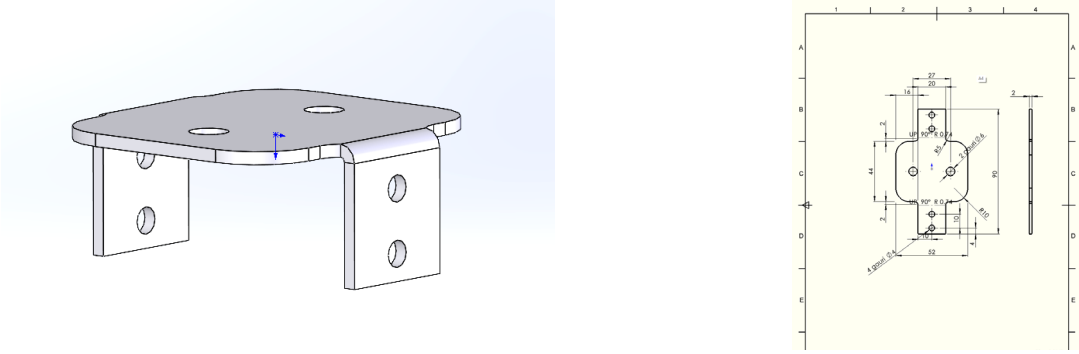
the evaluation of the higher-order natural modes of the motor mount, especially in the case of lightweight aluminum structures, where low damping may favor the amplification of high-order vibrations.

Consequently, including the ESC PWM frequency among the analyzed parameters contributes to a more comprehensive assessment of the vibrational excitation spectrum and justifies the extended frequency range adopted in the numerical modal analysis.

Motor Mount Geometry and Material Configurations

The analyzed structural component is the motor mount, which serves as the interface between the electric motor and the drone arm and plays a critical role in transmitting dynamic loads to the main structure. For this reason, the motor mount is particularly sensitive to the occurrence of resonance phenomena.

In the first stage, the motor mount was manufactured from aluminum, a material selected to reduce the overall mass of the drone and improve energy efficiency. However, during operation, structural cracks were observed in the areas around the mounting holes and the bent regions, indicating the onset of vibration-induced fatigue.



a) 3D motor mount **b) 2D motor mount**

Fig. 3 – Drone motor mount

Numerical Modeling and Modal Analysis

The modal analysis of the motor mount was performed using the finite element method, following a clear sequence of steps to ensure that the obtained results are reproducible and engineering-relevant. The adopted methodology was identical for both analyzed configurations—aluminum and steel motor mounts—with differences introduced exclusively through the material properties.

The first stage consisted of importing and verifying the three-dimensional geometry of the motor mount, based on the CAD model used in the construction of the real prototype. The geometry was inspected to eliminate topological errors and to ensure surface continuity in the bending, mounting, and stiffening regions, which play a critical role in the dynamic behavior of the component.

Material Definition – Input Data

Two distinct sets of material properties were defined for the modal analysis:

• Aluminum

- Elastic modulus: ~70 GPa
- Density: ~2730 kg/m³
- Poisson's ratio: 0.39

• Steel

- Elastic modulus: ~210 GPa
- Density: ~7800 kg/m³
- Poisson's ratio: 0.28

The materials were considered linear elastic and isotropic, and structural damping was not included in the model, since the objective of the analysis was to determine the natural frequencies and mode shapes rather than to evaluate vibration response amplitudes.

Boundary Conditions and Computational Assumptions

A shell-type mesh was used to discretize the motor mount geometry, which is appropriate for bent sheet-metal components where the thickness is small compared to the in-plane dimensions. This choice provided good accuracy in stiffness prediction at a reduced computational cost.

The main discretization parameters were:

- Mesh type: curvature-based blended mesh
- Maximum element size: ~2.32 mm
- Minimum element size: ~0.56 mm
- Total number of nodes: ~3200
- Total number of elements: ~1500

The same discretization was applied to both material variants in order to eliminate the influence of the mesh on the comparison of results.

Modal analysis was carried out using the FFEPlus solver, and the first five natural vibration modes were extracted for each configuration. The analyzed frequency range was selected to allow correlation with the excitation frequencies generated by the drone propulsion system.

Post-Processing of Results

The modal analysis results were evaluated in terms of:

- natural frequency values;
- mode shapes associated with each mode;
- distribution of maximum displacements;
- zones of deformation concentration.

Special attention was given to the regions around the mounting holes and bent edges, as these represent potential crack initiation points. The comparison between aluminum and steel configurations allowed a direct assessment of the influence of material selection on the dynamic behavior of the motor mount.

RESULTS

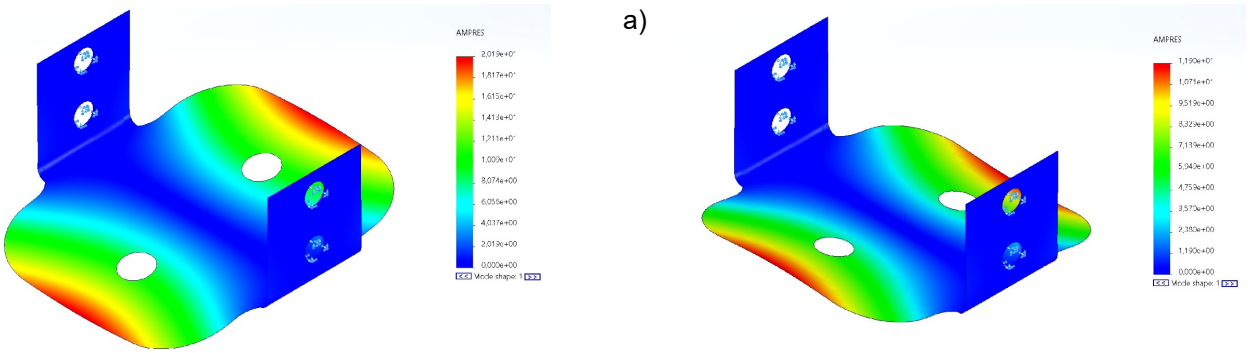
The modal analysis of the motor mount was performed for two structural materials: EN-AW 3003 aluminum alloy and S235JR structural steel, using the same geometry, identical boundary conditions, and the same FEM discretization. This approach allows a direct comparison of the dynamic behavior of the structure solely as a function of the material.

Modal behavior of the EN-AW 3003 motor mount

The first natural mode *(Fig. 4a, left)* is dominated by a global bending of the support plate. Maximum displacements occur at the free edges of the lower plate, while the vertical mounting flanges remain almost rigid. The maximum amplitude reaches approximately 20 mm, indicating low bending stiffness. Regions with high deformation gradients are located at the transitions between flat and bent areas, promoting stress concentration and crack initiation.

The second mode *(Fig. 4b, left)* is characterized by a combined torsional and bending deformation, in which the two ends of the mount move in opposite directions. Maximum amplitudes of approximately 18 mm are observed along the lateral edges and around the central mounting holes. This mode is particularly critical because it induces large alternating stresses around the mounting holes, which are precisely the regions where cracks are observed during operation.

The third mode *(Fig. 4c, left)* exhibits a higher-order bending behavior, with alternating rigid and flexible regions across the plate surface. Maximum displacements of approximately 22.5 mm occur at the corners and edges, producing large deformation gradients in the geometric transition areas. This mode contributes significantly to the vibration-induced fatigue of the EN-AW 3003 material.



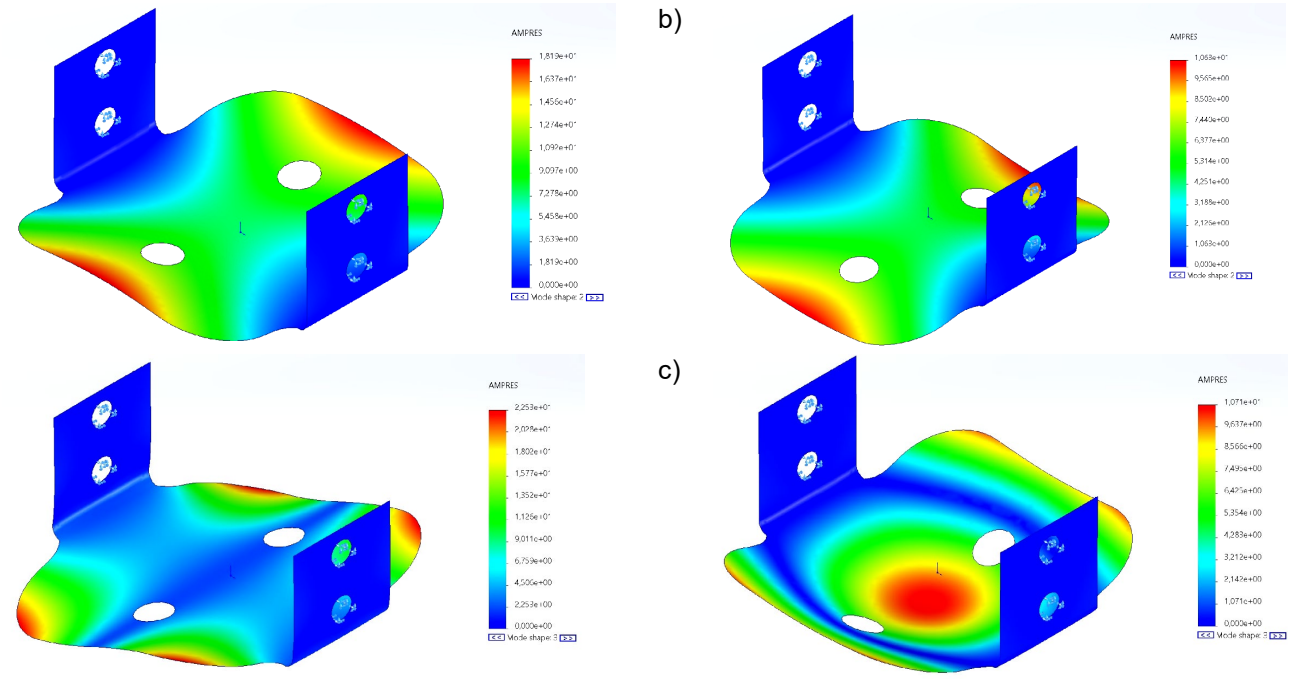


Fig. 4 Modal behaviour of the motor mount
EN-AW 3003 – left and S235JR – right

Modal behavior of the S235JR motor mount

Mode 1 – Global bending mode (f_1 = 2278.7 Hz) *(Fig. 4a, right)* The mode shape is similar to that of the aluminum configuration; however, the vibration amplitudes are significantly reduced. The maximum displacement decreases to approximately 11.9 mm, corresponding to a reduction of about 41%. The lower plate exhibits much higher stiffness, and the deformation concentration zones are substantially attenuated.

Mode 2 – Torsional–bending coupled mode (f_2 = 2480.5 Hz) *(Fig. 4b, right)* In this mode, the steel motor mount shows superior torsional stiffness, with a maximum amplitude of approximately 10.6 mm, more than 40% lower than in the aluminum case. The regions around the mounting holes are no longer dominant deformation zones, significantly reducing the risk of cracking.

Mode 3 – Higher-order bending mode (f_3 = 5887.2 Hz) *(Fig. 4c, right)* This higher-order mode exhibits a more uniform displacement distribution, with a maximum amplitude of approximately 10.7 mm, representing a reduction of more than 50% compared to EN-AW 3003. This indicates improved structural damping and increased overall stiffness of the assembly.

The direct comparison of mode shapes and amplitudes clearly shows that EN-AW 3003 leads to a more flexible structure, characterized by large displacements and localized deformation concentrations that promote vibration-induced fatigue. In contrast, S235JR increases dynamic stiffness, shifts the natural frequencies to higher values, and reduces vibration amplitudes by 40–50%, effectively eliminating the vibration amplification mechanism responsible for crack formation.

These results demonstrate that for high-power agricultural drones, dynamic material optimization is a decisive factor, and the use of structural steel provides a robust solution for preventing resonance phenomena and structural degradation.

The modal analysis of the motor mount was performed for two structural materials—EN-AW 3003 aluminum alloy and S235JR structural steel—using the same geometry, boundary conditions, and FEM discretization. This approach enables a direct evaluation of the influence of material selection on dynamic behavior.

Natural frequencies

The results show that for all analyzed modes, the steel motor mount exhibits higher natural frequencies than the aluminum variant. The increase is more pronounced for Modes 1 and 5, which are the most relevant from the perspective of dynamic excitation.

This increase is a direct consequence of the much higher stiffness of steel (E = 210 GPa compared to 70 GPa for aluminum), which compensates for the increase in mass.

Tabel 2

The first five natural frequencies obtained

Mod	EN-AW 3003 [Hz]	S235JR [Hz]	Increase (%)
1	2192.7	2278.7	+3.9 %
2	2427.6	2480.5	+2.2 %
3	5828.5	5887.2	+1.0 %
4	5963.9	6062.1	+1.6 %
5	5979.0	6240.6	+4.4 %

Modal mass participation indicates the dominant vibration directions:
EN-AW 3003
Sum of modal participations:

- X = 0.049
- Y = 0.616
- Z = 0.00033

The dominant mode is Mode 2 (2427 Hz), with 57% of the modal mass in the Y direction (vertical), indicating a bending-type vibration of the motor mount.
S235JR
Sum of modal participations:

- X = 0.063
- Y = 0.616
- Z = 0.00031

The steel structure exhibits the same dominance along the Y-axis, but with a greater redistribution toward the X direction in the higher modes (Mode 4), which indicates improved torsional and combined bending–torsional stiffness.
Modal amplitudes

Tabel 3

The maximum values of the modal amplitudes are

Mod	EN-AW 3003 (mm)	S235JR (mm)	Reduction
1	20.19	11.90	−41 %
2	18.19	10.63	−42 %
3	22.53	10.71	−52 %
4	24.89	12.77	−49 %
5	18.16	14.41	−21 %

Steel leads to a reduction of vibration amplitudes between 40 and 52%, which results in much lower cyclic stresses in the regions of stress concentration.
For the EN-AW 3003 configuration, the first two natural modes (≈ 2.2–2.4 kHz) are characterized by:

- large deformations in the mounting-hole regions,
- maximum displacements at the bent edges, confirming favorable conditions for the initiation of vibration-induced fatigue cracks.

In the S235JR configuration, the same modes occur at higher frequencies and with much smaller amplitudes, resulting in:

- increased stiffness of the motor mount,
- improved structural energy dissipation,
- a significant reduction in resonance risk.

The KDE 5215XF motors operate in the range of:

- fundamental rotational frequency ≈ 190 Hz,
- blade-passing frequency ≈ 380 Hz,
- harmonics up to approximately 600–800 Hz.

Although the natural frequencies of the motor mount are much higher than these values, the aluminum support exhibits more flexible modes that are susceptible to high-order harmonic excitation and vibrational coupling with the drone arm.

By using S235JR steel, high-order resonance is better attenuated and vibration amplitudes are drastically reduced, which explains the disappearance of cracks during operation.

CONCLUSIONS

The modal analysis of the motor mount based on the real materials EN-AW 3003 and S235JR clearly demonstrated the decisive influence of material selection on the dynamic behavior of the structure. Although both configurations exhibit natural modes in the kHz range, differences in stiffness and structural damping lead to significantly different vibrational responses.

The motor mount made of EN-AW 3003 exhibits lower natural frequencies and high modal amplitudes, with maximum values reaching approximately 25 mm in the mounting-hole regions and at the bent edges. The modal mass distribution shows a strong dominance in the Y direction (vertical bending), which explains the occurrence of large cyclic stresses in these areas. These characteristics confirm the high susceptibility of the aluminum structure to vibration-induced fatigue and crack initiation, as also observed in real operation.

By replacing the material with S235JR structural steel, the natural frequencies were systematically shifted to higher values, and vibration amplitudes were reduced by 40–50% for the first four modes. The increased structural stiffness (E = 210 GPa) resulted in much better dynamic stability, with a more uniform deformation distribution and the elimination of critical displacement concentrations in the mounting regions.

The results demonstrate that for high-power agricultural drones, mass reduction achieved through the use of aluminum alone is not sufficient to ensure dynamic reliability. For components directly exposed to motor and propeller excitations, such as motor mounts, the dominant design criterion must be dynamic stiffness and resistance to vibration-induced fatigue, rather than mass alone.

Therefore, the use of S235JR for the motor mount represents a superior constructive solution, providing:

- a significant reduction in vibration amplitudes,
- increased structural service life,
- elimination of resonance-induced cracking risk.

The applied methodology—FEM-based modal analysis using real material properties—offers an effective tool for the design and validation of vibration-critical UAV structures and can be extended to the entire architecture of agricultural drones.

ACKNOWLEDGEMENT

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ADDITION TO THE STATISTICS OF SOME EXPERIMENTAL DATA
/
SUPLIMENTE LA STATISTICA UNOR DATE EXPERIMENTALE

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Keywords: *additions, results, research, experimental, efficiency, fertilizers*

ABSTRACT
The article presents additions to the statistical processing of the results of the experimental research carried out in an experimental field in India and presented in the source article. The source article contains experimental data regarding the effectiveness of some treatments with bio-fertilizers on the garlic crop. The authors of the article above present the main results and minimal statistical processing. By decoding the definitions of the treatments, we added a regression analysis in which the quality parameters proposed by the authors of the original work become linear functions of three independent variables. Regression functions are useful for interpolating data in the three-dimensional field of independent variables and for searching for optimal points. The regressions also explain the extent to which the independent variables influence the quality parameters of the crop. Other additional results presented in the article are correlation, coefficient of variation, scoring method, outliers, cluster analysis, and significance tests. All the statistical analysis methods proposed for estimating the effectiveness of garlic fertilization treatments indicated the same winning treatments as the analysis of the authors of the original article. The proposed methods strengthen the authors' conclusions and broaden the knowledge about the experiment performed. Expanding knowledge also involves a series of new questions capable of generating a new, more extensive experimental plan that will provide additional answers on the soil-plant-fertilizing substance interaction.

REZUMAT
Articolul prezintă completări la prelucrarea statistică a rezultatelor cercetării experimentale efectuate într-un câmp experimental din India și prezentate în articolul sursă. Articolul sursă conține date experimentale privind eficacitatea unor tratamente cu bio îngrășăminte asupra culturii de usturoi. Autorii articolului de mai sus prezintă principalele rezultate și procesări statistice minime. Prin decodificarea definițiilor tratamentelor, am adăugat o analiză de regresie în care parametrii de calitate propuși de autorii lucrării originale devin funcții liniare a trei variabile independente. Funcțiile de regresie sunt utile pentru interpolarea datelor în câmpul tridimensional al variabilelor independente și pentru căutarea punctelor optime. Regresiile explică și măsura în care variabilele independente influențează parametrii de calitate ai culturii. Alte rezultate suplimentare prezentate în articol sunt corelația, coeficientul de variație, metoda de punctare, valorile aberante, analiza clusterului și testele de semnificație. Toate metodele de analiză statistică propuse pentru estimarea eficacității tratamentelor de fertilizare ale usturoiului au indicat aceleași tratamente câștigătoare ca și analiza autorilor articolului original. Metodele propuse întăresc concluziile autorilor și lărgesc cunoștințele despre experimentul efectuat. Extinderea cunoștințelor implică și o serie de întrebări noi capabile să genereze un plan experimental nou, mai amplu, care va oferi răspunsuri suplimentare privind interacțiunea sol-plantă-substanță fertilizantă.

INTRODUCTION

The increase in the number of articles that present the results of experimental or theoretical-empirical research in the literature is a beneficial phenomenon and expands the area of knowledge. Moreover, regarding the fields of agricultural research, the experiment is the most common and productive method for obtaining new knowledge and applying it in agricultural operations. On the other hand, the horizon of knowledge widens somewhat chaotically. Results are obtained with narrow fields of application, which solve local problems in time and space. There is no concern for the coordination of the results of these researches, with a generalization tendency, which would create the premises for the emergence of theories with satisfactory generality, applicable to many particular cases. The review-type works are sometimes a

start for such attempts, but they have more of an exposition character, not a synthesis of the results. In (*Parolini, 2015*). it was stated that "Agricultural experimentation is a world in constant evolution, spanning multiple scientific domains and affecting society at large." Along the same line of increasing the amount of literature, many works have appeared, generally well-intentioned and even partially well-made, which, however, do not sufficiently capitalize on the experimental results, (*Bhushan et al., 2020*). Satisfactory exploitation of experimental data means not only an ANOVA analysis or a regression analysis.

The statistical results must be interpreted clearly, even if some estimators are very well known because new sources of inspiration can result from the opinions of some authors. Also, some results can be extended to the numerical domain, by decoding the experimental codes, which leads to obtaining the parametric spaces that can be easily processed together with the numerical results already published. In this sense, we have published the papers (*Cardei, 2024 DOI: 10.13140/RG.2.2.16479.84647; Cardei, 2024 DOI: 10.13140/RG.2.2.34926.63049; Cardei, 2024 DOI: 10.13140/RG.2.2.14003.44325; Cardei, 2024 DOI: 10.13140/RG.2.2.18925.60645*),.

This article presents the results of research of the same type as the previously mentioned articles. As in the case of the aforementioned articles, the research started by decoding the names (codes) of some treatments for fertilizing the garlic crop and selecting the most convenient of these treatments. By decoding the treatment recipes (which can be considered their codes), statistical models can be obtained using regression analysis. The regressions confirm at a higher level the results obtained by the authors (*Bhushan et al., 2020*). In addition, they can make interpolations on values that were not included among those used in the experiments for the independent variables (predictors).

The regressions can be used in attempts to optimize the quality parameters of the garlic crop, depending on the values of the independent variables that represent the doses of fertilizing substances administered in the case of each treatment. Isolated optimal points can be obtained using non-linear regressions. Obtaining non-linear regressions is conditioned by the choice of extreme values of the doses that produce effects of diminishing the increase of some quality parameters, for example (*Piepho and Edmondson, 2018*).

The additions to the article (*Bhushan et al., 2020*) also included other statistical tools highlighting and/or reinforcing the significant performances of some treatments to others. The proposed tools are correlation, coefficient of variation, regression analysis, score method, outliers, cluster analysis, and significance tests. We also proposed a series of other analyses based on many qualitative parameters of the garlic harvest and environmental components (soil, water), for which we do not have enough data to make them concrete. The proposals are useful for the development of future experimental plans, (*Zubair, 2023*).

The accumulation of all the additions presented in this paper is a confirmation and reinforcement of the authors' conclusions (*Bhushan et al., 2020*) because the results are convergent. Therefore, the research described in the paper is both intensive (gathers results that confirm the authors' conclusion (*Bhushan et al., 2020*), strengthening it) and extensive (brings new knowledge about treatments and their properties, but also about possible experimental extensions).

The points of view exposed above and the importance of experimental research are supported by many more general assessments on the subject, (*Green and Gerber, 2004; Em, 2024; Zubair, 2023; Thomas, 2021; Leonelli, 2013; Bullock et al., 2019; Mesa-Vasquez et al., 2021; Piepho et Edmondson, 2018*). Last but not least, the intensive processing of experimental data highlights unethical practices and even experimental fraud (*Resnik et al., 2017*).

In (*Green and Gerber, 2004*) it is stated: The results from large-scale field experiments command unusual attention in both academic circles and the public at large. Although every experiment has its limitations, field experiments are widely regarded as exceptionally authoritative. By combining the power of randomization with the external validity of field research, these studies have the potential to eclipse or significantly bolster findings derived from laboratory experiments or non-experimental research.

Further contributing to the strength of field experimentation is the transparent manner in which the data are analysed. In contrast to non-experimental data analysis, in which the results often vary markedly depending on the model the researcher imposes on the data and in which researchers often fit a great many models in an effort to find the right one, experimental data analysis tends to be quite robust. Simple comparisons between control and treatment groups often suffice to give an unbiased account of the treatment effect, and additional analysis merely estimates the causal parameters with greater precision. This is not to say that experimental research is free from data mining, but the transformation of raw data into statistical results involves less discretion and therefore fewer moral hazards.

The contributions of this article to the more intensive processing of experimental data published in (*Bhushan et al., 2020*) are in accord with the modernization of experimental research in agriculture.

The authors (*Voors et al., 2016*) show that "Throughout the (developing) world, experiments are now being used, both a measurement tool to assess preferences and behaviour and a method to separate cause and effect."

MATERIALS AND METHODS

The material of this article consists of the research results described in (*Bhushan et al., 2020*). Some statistical methods are presented with the help of which the results from (*Bhushan et al., 2020*) are completed. Interpretations and comments on the results and analysis methods used are also formulated.

The problem that must be solved is the estimation of the effects of bio-fertilizer treatments, applied to an agricultural crop (garlic) so that the quality parameters of the crop are optimized (in this case, five quality parameters that must all be maximized). The experiment, described in (*Bhushan et al., 2020*), provided several three repetitions.

The authors (*Bhushan et al., 2020*) highlight the most effective treatments only from the point of view of descriptive statistics (minimum and maximum values). Another statistical estimator, often used in agricultural research (CD), appears in the last row of Table 1 in (*Bhushan et al., 2020*).

The authors (*Bhushan et al., 2020*), like many other authors, extract this value from ANOVA analyses, they do not give the name (Critical difference or Critical dispersion?), the definition or the method of calculation. Moreover, the authors (*Bhushan et al., 2020*) do not even explain how they use the CD value to estimate the treatment effect on the quality parameters of the garlic crop. If by CD we mean Critical difference, then according to its definition (for example (*https://testbook.com/question-answer/in-least-significant-difference-lsd-test-the-cri--638470752b26374654a206df, Testbook)*) it follows that in this analysis it is used to ensure the correct performance of the repetitions by comparing the means. Through this, the authors can motivate the hypothesis that the results of the experiments are not random. The series of fifteen values corresponding to the five qualitative parameters of the garlic crop thus, hypothetically, avoids a random character.

The main question that remains is how reliable are the assessments (the place in the rankings of the treatments) within the series of each qualitative parameter. More precisely, are the values corresponding to various treatments far enough apart so that randomness is avoided? To answer this question, we used the method of correlations, the method of the coefficient of variation, the method of regressions, the method of scores, the method of box plot representations, the method of cluster analysis, and the calculation of statistical significance. For the next calculations, the experimental input data are arranged as in Table 1.

Table 1

Arrangement of experiment input data

Treatment	FYM[a] Kg/ha	RDF[b], kg/ha			Azobactor Kg/ha	PSB[c] Kg/ha	VAM[d] Kg/ha
		N	P	K			
T_0	20000	100	50	50	0	0	0
T_1	20000	100	50	50	6	0	0
T_2	20000	100	50	50	8	0	0
T_3	20000	100	50	50	0	6	0
T_4	20000	100	50	50	0	8	0
T_5	20000	100	50	50	0	0	6
T_6	20000	100	50	50	0	0	8
T_7	20000	100	50	50	6	6	6
T_8	20000	100	50	50	6	8	8
T_9	20000	100	50	50	6	6	8
T_{10}	20000	100	50	50	6	8	6
T_{11}	20000	100	50	50	8	6	6
T_{12}	20000	100	50	50	8	8	8
T_{13}	20000	100	50	50	8	6	8
T_{14}	20000	100	50	50	8	8	6

[a] FYM – Farm Yard Manure, [b] RDF – Recycling-derived fertilisers, [c] PSB - Phosphate solubilising bacteria, [d] VAM – Vesicular Arbuscular Mycorrhizal

In the following, az, psb and vam will be noted, the independent variables that represent the doses of azobactor, PSB and VAM, in Kg/ha. For the five quality parameters (dependent variables) the notations Ph

(for Plant height, cm), Nol (for Number of leaves), Dps (Diameter of pseudo-stem, cm), Wt (Weight of bulb/plant, g), Ypp (Yield per plot, kg). I respected the units of measure used by the authors (*Bhushan et al., 2020*) to make the numerical links with the original results easier and, on the other hand, because it allows working with reasonable numbers as an order of magnitude.

RESULTS

The additional results obtained compared to those given by the authors (*Bhushan et al., 2020*), which evaluate the effectiveness of the treatments from descriptive statistical analyses (maximum and minimum values), contain correlation analysis, coefficient of variation analysis, regression analysis, score method, calculation of outliers, and analysis clusters, significance tests. At the end of the chapter, other possible analyses are suggested, for which the existing data are not enough.

Correlations

The Pearson correlation coefficients, (*Koroliouk, 1983*), between the dependent variables and the independent variables (predictors) are given in Table 2.

Table 2

Pearson correlation coefficients between dependent and independent variables

	Ph	Nol	Dps	Wt	Ypp
az	0.733	0.726	0.554	0.613	0.659
psb	0.717	0.682	0.571	0.676	0.652
vam	0.617	0.665	0.558	0.614	0.572

The Pearson correlation coefficients suggest the most intense links between the variables of the experimental model established by the authors (*Bhushan et al., 2020*). The suggestions are used in chapter 2.3 and commented on in chapter 3.

Coefficient of Variation

Evidence of the superiority of certain treatments compared to the others applied, through the quality parameters of the crops, is necessary to indicate superior treatment to others. To facilitate this assessment, I use, in this subchapter, the coefficient of variation of the statistical series, CV, (*Everitt, 1998*). According to (*https://www.6sigma.us/six-sigma-in-focus/coefficient-of-variation/ Coefficient of Variation: Mastering Relative Variability in Statistics*) a CV less than 1 (or 100% when expressed as a percentage) is considered low variability, while values greater than 1 suggest high variability. Appreciating the behaviour of a series depends on the context.

Thus, according to (*https://www.6sigma.us/six-sigma-in-focus/coefficient-of-variation/ Coefficient of Variation: Mastering Relative Variability in Statistics*) in production environments where precision is paramount, a CV below 0.1 (or 10%) can be considered acceptable (according to (*http://sorana.academicdirect.ro/pages/doc/TD2014/Curs04.pdf, Statistica descriptiva*), the series is homogeneous), while in financial modelling or risk analysis, a CV exceeding 0.3 (or 30%, or following (*http://sorana.academicdirect.ro/pages/doc/TD2014/Curs04.pdf, Statistica descriptiva*), the series is heterogeneous/heterogeneous) could be considered high risk. Also in (*https://www.6sigma.us/six-sigma-in-focus/coefficient-of-variation/ Coefficient of Variation: Mastering Relative Variability in Statistics*), it is noted that when the mean of a data set approaches zero, the coefficient of variation can become sensitive to small fluctuations, which can lead to misleading or unreliable interpretations. In such cases, it is advisable to supplement the CV analysis with other statistical measures or subject matter expertise.

In the case of experiments that compare treatment variants, the highlighting of a variant is done by significantly higher values for certain treatments, which differentiate them from the others, otherwise, it is not possible to make a clear recommendation of the treatments with maximum or minimum values of the parameters of quality.

Therefore, according to (*https://www.6sigma.us/six-sigma-in-focus/coefficient-of-variation/ Coefficient of Variation: Mastering Relative Variability in Statistics*), to highlight a treatment significantly superior to the others, we would expect a CV with values higher than 0.3 or 30%. For the experiment referred to in the article, the coefficients of variation of the quality parameters are given in Table 3.

Table 3

Coefficients of variation of the quality parameters

	Ph	Nol	Dps	Wt	Ypp
Maximum value	79.830	9.860	1.130	38.030	5.960
Minimum value	73.760	6.300	0.660	27.300	5.090
Control value	73.760	6.300	0.660	27.300	5.090
Average value	76.326	7.754	0.843	31.757	5.391
The ratio between amplitude and control	0.082	0.565	0.712	0.393	0.171
CV	0.025	0.142	0.140	0.094	0.044

For the ratio between amplitude and control is used the formula:

$$Ram = \frac{max - min}{control} \quad (1)$$

where max and min are the maximum and minimum values of the series, and $control$ is the series value for the control treatment.

Regressions

The expressions of the linear regressions and the estimates of the interpolation errors are given in Table 4. The coefficient of determination, $R^2$and the measure of the interpolation error

$$\varepsilon = \sqrt{\frac{\sum_{i=1}^{n}(\hat{\theta}_i - \theta_i)^2}{n}} \quad (2)$$

where n is the sample size (number of data), $\hat{\theta}_i$, is the value calculated by interpolation regression, and θ_i, is the experimental value of the random variable θ (in this case, Ph, Nol, Dps, Wt sau Ypp) with index i, are given in the same table.

Table 4

Linear regressions of crop quality parameters

no	regression	R^2	ε	source
1	$Ph = 73.244 + 0.260az + 0.246psb + 0.155vam$	0.825	0.797	[15]
2	$Ph = 73.571 + 0.302az + 0.288psb$	0.760	0.925	[15],[27]
3	$Nol = 5.967 + 0.146az + 0.123psb + 0.114vam$	0.820	0.467	[15],[27]
4	$Dps = 0.687 + 0.011az + 0.012psb + 0.011vam$	0.538	0.080	[15]
5	$Dps = 0.751 + 0.020psb$	0.330	0.097	[15], [27]
6	$Wt = 27.309 + 0.288az + 0.376psb + 0.289vam$	0.693	1.656	[15]
7	$Wt = 28.987 + 0.593psb$	0.460	2.201	[15], [27]
8	$Ypp = 5.043 + 0.028az + 0.028psb + 0.019vam$	0.682	0.133	[15]
9	$Ypp = 5.083 + 0.033az + 0.033psb$	0.620	0.144	[15], [27]

Scoring Method

The scoring method was elaborated for research in the financial field, based on notaries of the performances of some entities. The definition and explanations about the scoring method can be found in various research materials from the financial, medical, linguistic, etc. fields, for example (*Reynolds et al., 2021*); *https://www.bumc.bu.edu/facdev-medicine/files/2011/01/scoring_system_and_procedure.pdf, Scoring System and Procedure*).

To obtain a ranking of the treatments applied to the garlic crop, the values of the quality parameters from Table 1 of the article (*Bhushan et al., 2020*) are normalized (so that the absolute size does not influence the calculation results), and then they are ordered in descending order. This is how Table 5 is obtained.

Table 5

The descending order of treatments for each of the five qualitative parameters

Treatment	Plant height,	Treatment	Number of leaves	Treatment	Diameter of pseudo-stem,	Treatment	Weight of bulb/plant,	Treatment	Yield per plot,

	cm				cm		g		kg
T_{12}	79.83	T_{12}	9.86	T_{12}	1.13	T_{12}	38.03	T_{12}	5.96
T_8	78.93	T_8	9.56	T_8	1.00	T_8	37.03	T_8	5.71
T_7	78.20	T_{10}	8.90	T_7	0.96	T_{10}	35.73	T_{10}	5.66
T_{10}	78.10	T_{13}	8.53	T_{10}	0.93	T_7	33.03	T_{13}	5.56
T_{13}	77.83	T_7	8.36	T_{13}	0.90	T_{13}	32.43	T_7	5.45
T_{14}	77.23	T_{14}	8.10	T_2	0.83	T_{14}	32.03	T_{14}	5.43
T_{11}	76.60	T_{11}	7.96	T_4	0.83	T_{11}	31.56	T_{11}	5.36
T_9	76.13	T_9	7.80	T_{14}	0.83	T_9	31.16	T_2	5.35
T_2	75.90	T_2	7.46	T_6	0.80	T_2	30.73	T_9	5.30
T_4	75.53	T_4	6.93	T_{11}	0.80	T_4	30.13	T_4	5.28
T_1	74.46	T_6	6.93	T_1	0.76	T_6	29.80	T_1	5.21
T_6	74.40	T_1	6.76	T_5	0.76	T_1	29.40	T_6	5.21
T_5	74.16	T_5	6.46	T_9	0.76	T_5	29.13	T_5	5.15
T_3	73.83	T_3	6.40	T_3	0.70	T_3	28.86	T_3	5.14
T_0	73.76	T_0	6.30	T_0	0.66	T_0	27.30	T_0	5.09

It can be seen in Table 5 that the T_{12} treatment has the most intense effect for all five quality parameters of the crop. In second place for each quality parameter is the T_8 treatment. Starting from the third place, there are variations in the order of the effectiveness of the rest of the treatments, that is, the order of the effects is no longer constant. As a first impression, there is a very high probability that the T_{12} and T_8 treatments are the most effective and, therefore recommendable to farmers (as an effect, not necessarily from an economic point of view).

The calculation example proposed in this paper gives 15 points to the winning treatment for each qualitative parameter (see Table 5) and, in descending order, to the other treatments 14, 13, ... points, the last one as efficiency receiving one point. The points earned for each qualitative parameter are accumulated directly, linearly or weights are applied depending on the beneficiary's interest in one or more qualitative parameters.

If the interest in quality parameters is equal, the ranking shown in Figure 1 is obtained. The T_{12} treatment wins for every quality parameter, followed by the T_8 treatment. The T_{12} treatment is the winner in (*Bhushan et al., 2020*), having the best values for all qualitative parameters, followed by the T_8 treatment.

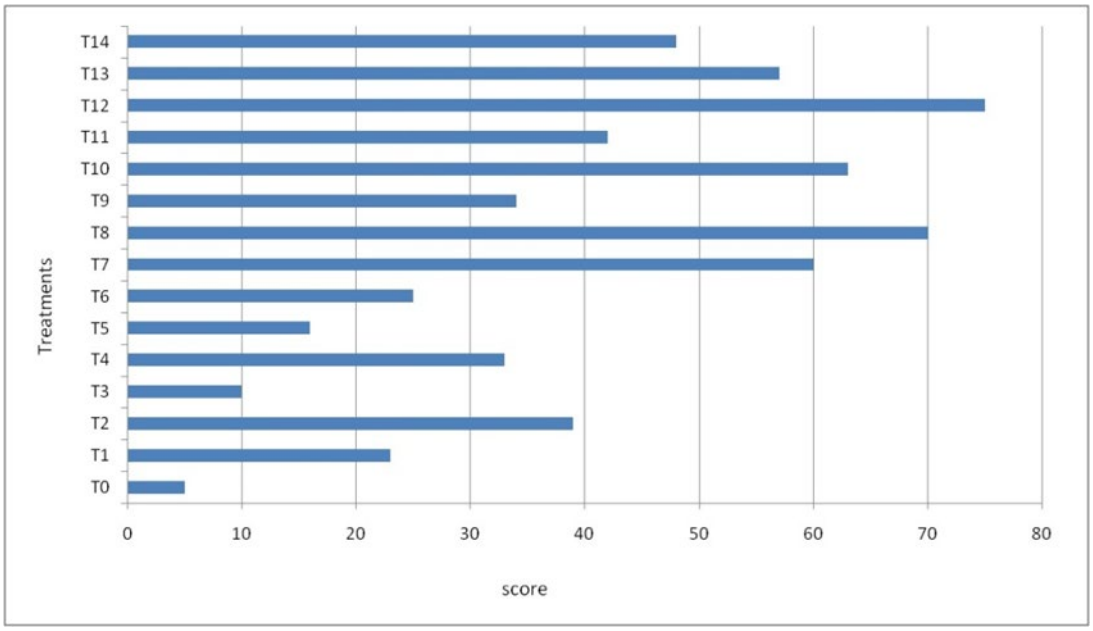


Fig. 1 - Graphic representation of the scores recorded by the treatments applied to the garlic crop

Outliers

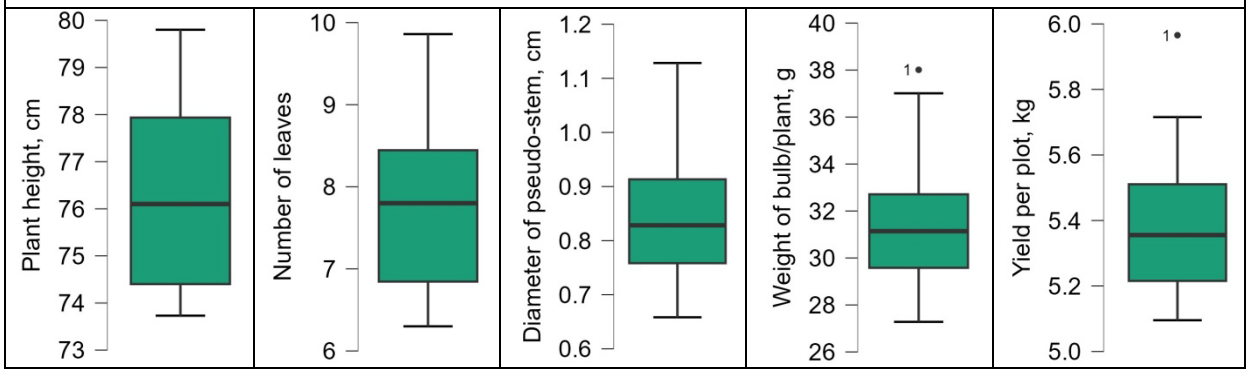
Another statistical notion that can contribute to strengthening the hypothesis that a certain treatment is most likely the most successful among those tested, is the outlier. The definition of the outlier given by (*https://openstax.org/books/statistics/pages/12-5-outliers, 12.5 Outliers; https://bookdown.org/pkaldunn/Book/identifying-outliers.html, 13.5 Identifying outliers*; *Aguinis et al., 2013;*

Sullivan et al., 2021) and the calculation methods proposed by the authors are accepted. If the outliers are calculated for the five qualitative parameters of the garlic crop subjected to treatments T_0, ..., T_{14}, using the program from the source (*https://www.statskingdom.com/, Statistics Kingdom*), based on the IQR method (the interquartile range) with k=1.5, outliers are found only for the parameters Weight of bulb/plant (38.03) and Yield per plot (5.96). Both outliers found are the maximum values and are achieved by the garlic crop treated with the T_{12} treatment. The fact that the two maxima are also outliers increases the probability that the order of the first values is the one found through experimentation.

Box plot representations for all five quality parameters of the garlic crop are given in Table 6, without asking for the representation of outliers. The outliers can be highlighted using the box plot graphic representations with the outliers representation option (Figure 2).

Table 6

Box plot diagrams for the series of quality parameters of the garlic crop subjected to the fifteen treatments



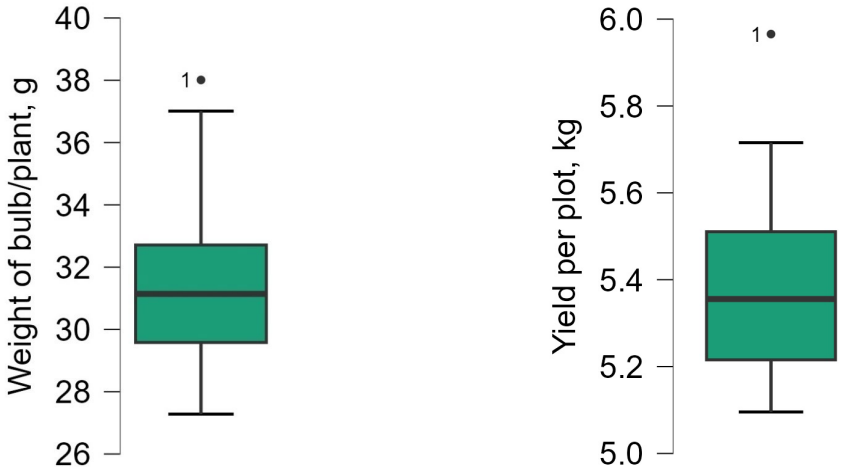


Fig. 2 - Box plot representations for quality parameters that show outliers

Cluster analysis

The definition of cluster analysis can be found in the literature, (*Tryon, 1939; Everitt, 2011; https://www.statistics.com/glossary/cluster-analysis/, Statistics*). We performed the calculations using the program from the source (*https://www.statskingdom.com/, Statistics Kingdom*). A way of displaying the results, for the case of the five performance parameters of garlic subjected to the treatments in (*Bhushan et al., 2020*), is shown in Figure 3. To make the cluster analysis results more visible, before the related calculation we normalized, (*https://despretot.info/ce-este-normalizarea/, Normalizare definitie. Normalizarea bazelor de date*) at unity the values of the five variables considered random, i.e. the qualitative parameters of the garlic crops.

This means that the elements of each random variable were multiplied by the sum of the elements of the random variable and then multiplied by 100, to express them in percentages.

It can be seen that the analysis gives a group (cluster) of superior results (united by the blue line, the envelopes of the blue line being the two dotted blue lines. The superior results group (cluster 1) contains the data that interests us for each of the five qualitative parameters of the garlic crop. In the upper cluster (1 on

Figure 3), the treatments T_{12} and T_8 are included, for each of the qualitative parameters of the crop. As a result, the cluster analysis indicates the same upper order of the treatments.

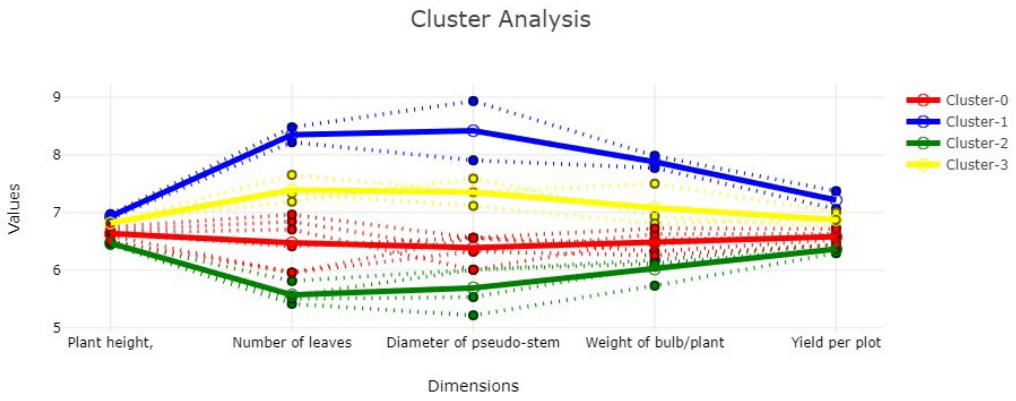


Fig. 3 - Graphic representation of cluster analysis results

Significance tests

If a ranking of the effectiveness of the treatments has been obtained, it remains to be established the extent to which the most effective treatment is significant compared to the other treatments. This means the answer to the question of whether the difference between the first places of the ranking is large enough so that we can state that the winning treatment is the most effective and that the order at the top of the ranking is not accidental.

The answer to this problem is given using significance tests, (*https://testbook.com/question-answer/in-least-significant-difference-lsd-test-the-cri--638470752b26374654a206df, testbook; https://analize-statistice.eu/despre-semnificatia-statistica/, Despre semnificaţia statistică*).

According to ((*https://testbook.com/question-answer/in-least-significant-difference-lsd-test-the-cri--638470752b26374654a206df, testbook*), the critical difference is calculated according to the formula:

$$CD = t(\alpha) \cdot df \cdot \sqrt{\frac{2 \cdot MSS}{n}} \quad (3)$$

where t is the value of the Student distribution for the significance level α (in our case 0.05), df is the number of degrees of freedom (I took df=n-1), n is the number of treatments (n=15), and MSS is the mean square of error. For the above data and the considered quality parameters, critical difference values from Table 7 were obtained.

Table 7

Critical difference values for the quality parameters considered by the authors

(Bhushan et al., 2020)

Quality parameter	CD
Ph	1.054
Nol	0.610
Dps	0.066
Wt	1.653
Ypp	0.130

Other analysis

The five quality parameters of the garlic crop used for the selection of the most effective treatment solutions are few for an overall analysis of the plant growth phenomenon.

An important category of quality parameters of garlic plants, which has not been taken into account in research, is that of the taste and health qualities of the plants. From the point of view of the content of chemical substances, both in the plants and in the soil left after harvesting, there is no data to be able to control the inclusion within acceptable or necessary limits.

Another category of important parameters for the management of agricultural farms is related to the economic performance of the harvest, to production costs. For this category of parameters, the authors formulated an answer through the cost-benefit ratio (C: B). The calculation method of this ratio is not argued in (*Bhushan et al., 2020*) and there are no detailed data on the data involved in the calculation of the C: B ratio values (for example (*https://project-management.info/benefit-cost-ratio/, Benefit cost ratio -BCR*)) given for the most effective treatments T_{12} and T_8. The importance of economic experiments in agriculture is emphasized in numerous articles, (*Mesa-Vasquez et al., 2021*).

For the data we have, a measure of the efficiency of the treatments can be calculated by dividing the values of the qualitative parameters by the amount of fertilizing substances consumed, which can be extracted from the definition of the treatments. The proposed ratio represents the amount of fertilizing substances used to obtain the quality parameter unit. The fertilizing substance consumed for each treatment is calculated using the data from Table 1, by simple summation. This calculation formula is the elementary view of a non-specialist.

The rankings obtained in this way show that the specific consumption of the quality parameter unit coincides with those given by the corresponding quality parameters. The only difference is that, in the case of specific consumption, minimization is of interest. Therefore, the two treatments (T_{12} and T_8) with the best qualitative performances are also the biggest consumers of substances, probably the most expensive.

A more refined estimate can be obtained by converting the quantity of substances used for treatments into money using the weighting of the quantities with the prices of the substances. In this way, a specific price per unit of quality parameter will be obtained. Cost estimation is important, as it is well appreciated in (*Zubair, 2023*), "Experimental research is a type of research that sometimes costs more than potential benefits or profits that are achievable when a favourable outcome is eventually reached".

Comments

The Pearson correlation coefficients (Table 2) show that the relationship between the dependent and independent variables is significant. The dependent variables Ph, Nol and Ypp depend on the predictors in the same order: az, psb, vam, while the dependent variables Dps and Wt depend on the predictors in the order psb, vam, az.

The study of the variation of the quality parameters shows that the minimum value is always in the control treatment, which means that the tested treatments helped the plants to obtain better performances. The coefficient of variation is lower than 0.3 for all quality parameters, which means a low variability. Our interpretation is that the CV does not clearly highlight a treatment through special qualitative performances. However, the existence of well-defined maximum values shows that among the tested treatments there are some that maximize certain qualitative parameters. Also, the ratio between amplitude and control highlights the existence of treatments that appreciably increase the values of the Nol and Dps parameters in relation to the values of the control tests.

The source (*https://www.statskingdom.com/, Statistics Kingdom*) show that results of the multiple linear regression 2 from Table 2, indicated that there was a very strong collective significant effect between the az, psb, vam, and Ph, ($F(2, 12) = 19.47$, $p < .001$, $R^2 = 0.76$, $R^2_{adj} = 0.73$). The individual predictors were examined further and indicated that az ($t = 3.567$, $p = 0.004$) and psb ($t = 3.398$, $p = 0.005$) were significant predictors in the model, and was no significant predictor in the model. The source (*Mathcad 14.0, 2007*) gives the same solution if we start with the predictors az and psb. Both sources (*Mathcad 14.0, 2007*) and (*https://www.statskingdom.com/, Statistics Kingdom*)) show that the vam predictor is insignificant for the dependent variable Ph. Using source (*Mathcad 14.0, 2007*) we considered all three predictors and obtained regression 1 from Table 2.

For the dependent variable Nol (Table 2, row 3), the two sources (*Mathcad 14.0, 2007*) and (*https://www.statskingdom.com/, Statistics Kingdom*), lead to the same conclusion. Results of the multiple linear regression indicated that there was a very strong collective significant effect between the az, psb, vam, and Nol, ($F(3, 11) = 16.72$, $p < .001$, $R^2 = 0.82$, $R^2_{adj} = 0.77$). The individual predictors were examined further and indicated that az ($t = 3.137$, $p = 0.009$) and psb ($t = 2.647$, $p = 0.023$) and vam ($t = 2.452$, $p = 0.032$) were significant predictors in the model.

Regarding the dependent variable Dps, the joint selection of sources (*Mathcad 14.0, 2007*) and (*https://www.statskingdom.com/, Statistics Kingdom*) (row 5, Table 2), shows that the results of the multiple linear regression indicated that there was a moderate collective significant effect between the az, psb, vam,

and Dps, (F(1, 13) = 6.28, p = .026, R^2 = 0.33, R^2_{adj} = 0.27). The following independent variables are not significant as predictors for dependent variable Dps: az, vam. Therefore, the calculator excluded these variables from the model. For the same dependent variable, source (*Mathcad 14.0, 2007*) can give a linear model dependent on all three predictors (Table 2, fourth row), with a better coefficient of determination but with rejection values (probabilities higher than 0.05) of all three coefficients of the predictors.

For the dependent variable Wt, source (*Mathcad 14.0, 2007*) states that results of the multiple linear regression indicated that there was a strong collective significant effect between the az, psb, vam, and Wt, (F(1, 13) = 10.92, p = 0.006, R^2= 0.46, R^2_{adj} = 0.41). So, the following independent variables are not significant as predictors for Wt: az, vam. Therefore, the calculator excluded these variables from the model. The full expressions (source (*Mathcad 14.0, 2007*)) and the dependence on the only significant predictor, for Wt, are given in Table 2 in rows 6 and 7.

Regarding the dependent variable Ypp, source (*Mathcad 14.0, 2007*) gives the regression expression from row 8 of Table 2, specifying that the results of the multiple linear regression indicated that there was a strong collective significant effect between the az, psb, vam, and Ypp, (F(2, 12) = 9.98, p = 0.003, R^2 = 0.62, R^2_{adj}= 0.56). The individual predictors were examined further and indicated that az (t = 2.521, p = 0.027) and psb (t = 2.465, p = 0.03) were significant predictors in the model, and was no significant predictor in the model. Also (*Mathcad 14.0, 2007*) specifies that the following independent variable is not significant as predictor for Ypp: vam. Therefore, it was excluded from the model. The complete expression of the linear regression (dependent on all three predictors) is given in row 9 of Table 2.

The selection based on the scoring method is based only on the values achieved by each treatment for each quality parameter of the garlic crop. The same two treatments, T_{12} and T_8, are winners in this order. Suppose the scores are calculated for the specific consumption of materials per quality parameter unit. In that case, the same ranking is found, which follows that the specific consumptions are also minimal for the winning treatments for the quality parameters (Table 8).

Table 8

The descending order of treatments for each of the five specific consumption per unit of qualitative parameters

Treat-ment	Specific Consume per Plant height, kg/(ha·cm)	Trea-tment	Specific Consume per Number of leaves, ha^{-1}	Treatment	Specific Consume per Diameter of pseudo-stem, kg/(ha·cm)	Treatment	Specific Consume per Weight of bulb/plant, kg/(ha·g)	Treatment	Specific Consume per Yield per plot, ha^{-1}
T_{12}	250.833	T_{12}	3174.603	T_{12}	30303.0303	T_{12}	732.6007		T_{12}
T_8	253.667	T_8	2959.467	T_8	26323.6842	T_8	680.4762		T_8
T_7	255.985	T_{10}	2682.038	T_7	24106.0241	T_{10}	651.0901		T_{10}
T_{10}	256.338	T_{13}	3125.938	T_{10}	28580.0000	T_7	693.2086		T_{13}
T_{13}	257.253	T_7	2887.157	T_{13}	24106.0241	T_{13}	664.0558		T_7
T_{14}	259.252	T_{14}	3096.904	T_2	26323.6842	T_{14}	686.7834		T_{14}
T_{11}	261.358	T_{11}	2887.157	T_4	25010.0000	T_{11}	671.4094		T_{11}
T_9	262.971	T_9	2394.498	T_{14}	20852.0833	T_9	606.0551		T_2
T_2	263.610	T_2	2094.351	T_6	20022.0000	T_2	540.6967		T_9
T_4	264.901	T_4	2566.667	T_{11}	26342.1052	T_4	642.4904		T_4
T_1	268.681	T_6	2249.438	T_1	21526.8817	T_6	560.3135		T_1
T_6	268.925	T_1	2515.075	T_5	25025.0000	T_1	634.3473		T_6
T_5	269.768	T_5	2030.832	T_9	17720.3539	T_5	526.5317		T_5
T_3	270.974	T_3	2347.245	T_3	22246.6667	T_3	617.3913		T_3
T_0	271.150	T_0	2471.852	T_0	24122.8916	T_0	625.1015		T_0

The search for the best-performing treatments can also be done by choosing those that achieve the maximum values, but especially by calculating the outliers. The same treatments won the competition by the method of box plot representations and by calculating the outliers (if there is also a function for setting the parameters of the calculation).

From the point of view of the significance level, values far apart in the series of qualitative parameters are not found, as shown by the CV values, chap. 2.2. Therefore, the selection of treatments from this point of view, is not relevant. As a result, the selection remains according to the parameters of the

descriptive statistics, especially the maximum value, but also, according to the score recorded by the treatments (subchapter 2.4).

The selection of the winning treatments can also be done after calculating the outliers (subjective because the operator must choose the tie-breaking factor, k), also after the cluster analysis, which has the same type of subjectivity.

The significance of the most effective treatments is calculated in chapter 2.7. For the Ph parameter, it is found that the winning treatment, T_{12}, indicates a significant plant height about all treatments, except for the T_8 treatment, which has the second value of the Ph parameter. Therefore, to decide between the two treatments, repetitions of the experience are still necessary, the event being able to be the generator of the current ranking. About the quality parameter Nol, the winning treatment, T_{12}, has an insignificantly different value compared to the value of the second-place treatment, T_8. The values of both treatments T_{12} and T_8 are significantly different compared to the third-place treatment, T_{10}. In the case of the Dps quality parameter, the difference between the values of the first two treatments in the ranking, T_{12} and T_8, has a significant value, exceeding the critical difference.

On the other hand, the difference between the two treatments, T_8 and T_7, is lower than the critical CD difference, therefore the relative ranking position of the T_8 and T_7 treatments is not certain. In the case of the quality parameter Wt, the difference between the first two treatments, T_{12} and T_8, and the difference between the second treatment and the third treatment, T_8 and T_{10}, are below the critical difference.

The difference between the values of the T_{12} and T_{10} treatments is, however, higher than the critical difference. As a result, the winning treatment T_{12} can be considered significant compared to all treatments, less than the second-placed treatment T_8. New experiments are needed for the final draw. For the quality parameter Ypp, the winning treatment, T_{12}, has a value of difference compared to the second-placed treatment T_8, greater than the critical difference. Consequently, the T_{12} treatment very likely wins the competition for the Ypp parameter.

Interpretations

The values of the *Pearson correlation coefficients* and the order of dependence of the predictor quality variables lead to the following observations: the plant height (Ph), number of leaves (Nol), and yield per plot (Ypp), depend more intensely on az and psb than from vam. Quality parameters Dps and Wt are most intensely influenced by psb, then vam and the least of az. According to the interpretation of the Pearson correlation coefficients, (*https://analize-statistice.eu/despre-semnificatia-statistica/, Despre semnificaţia statistică*), Table 2 shows that the dependent variables are correlated with the independent ones from moderate to strong correlation, (*Schober et al., 2018*). There are many conventions for interpreting the values of the Pearson correlation coefficient, (*Akoglu, 2018*). The conventions depend on the scientific field of application and the subject of the research.

According to (*http://sorana.academicdirect.ro/pages/doc/TD2014/Curs04.pdf, Statistica descriptiva*), taking into account the *CV* values for the five series of values of the quality parameters, the Ph, Wt, and Ypp series are homogeneous, and the Nol and Dps series are relatively homogeneous. It results that using *CV*, very high values of the quality parameters compared to the other values of the series are not highlighted. Therefore, the coefficient of variation, *CV*, does not show treatments superior to the others, within those tested. According to (*https://www.6sigma.us/six-sigma-in-focus/coefficient-of-variation/, Coefficient of Variation: Mastering Relative Variability in Statistics*) the coefficients of variation of the series of quality parameters being much lower than 1, the variability of these series is considered low. As a result, the clear highlighting of some winning treatments, in this way, has little chance of being achieved, in the case of the investigation (*Bhushan et al., 2020*).

The *regressions* obtained in chapter 2.3 are interpreted in chapter 3. The regression relationships show to what extent the predictors considered by the authors (*Bhushan et al., 2020)* in the experiments explain the variation of the quality parameters. In addition, I explained the role that the obtained regressions can have in identifying optimal points in the space of independent variables (predictors). The regressions also indicate the order of treatments as functions of three variables.

The score of the treatment, based on the rankings for each quality parameter, indicates the same winning treatments. Minimal rationing of substance consumption shows that the winning treatment is also the most substance-consuming, possibly the most expensive. Moreover, the almost perfect linearity of the calculation relationships, noticed from the regression calculation, at least relative to the considered range of

variation of the predictors, leads to equalization of the ratios between consumption and performance for each quality parameter. This observation makes it difficult to choose a treatment if we want to take into account the qualitative performances as well as the economic ones.

According to (*https://tipstrick.ro/analiza-valorilor-aberante-in-r-detectarea-si-eliminarea-valorilor-aberante/, Analiza valorilor aberante în R – Detectarea și eliminarea valorilor aberante*), in data analysis, outliers are observations that differ significantly from the rest of the data. These values may be caused by measurement errors, or data entry errors or may represent unusual real phenomena. Identifying and managing outliers is crucial in many applications, as they can significantly affect analysis results.

In the analysis presented in this paper, the calculation of outliers is done in the sense of looking for unusual real phenomena, which is, selecting some treatments with significantly higher efficiency than the other tested treatments.

We identified only two series that show outliers: those corresponding to the quality parameters Wt and Ypp (Table 6 and Figure 2). Each of these outliers is also the maximum value and indicates the winning treatment (T_{12}, as for the other three quality parameters).

Cluster analysis, also known as *clustering*, is a data mining method that groups similar data points. The purpose of cluster analysis is to divide a data set into groups (or clusters) so that data points in each group are more similar to each other than to data points in other groups, (*https://www.geeksforgeeks.org/data-mining-cluster-analysis/, Data Mining – Cluster Analysis*). We applied the cluster analysis to separate the suspicious treatments from the winning ones, forming suspicious groups with the optimal performance sought. When the group of maximum or minimum values (depending on which is of interest depending on the nature of the quality parameter) is formed by a single element, that treatment is recommended for application (the case of Wt and Ypp). But, if the groups of performing treatments contain two or more elements, then the experiments must be repeated with the refinement of the network of predictors (the independent variables) or other criteria must be used to detach them (the case of Ph, Nol and Dps).

We also used the significance tests to strengthen the decision on the winning treatments of the competition. In Chapter 3, I commented extensively on the statistical significance tests used. The results of the statistical significance tests confirmed the results of all the other analysis methods applied. The T_{12} and T_8 treatments are the most likely winners of the competition, a conclusion also stated by the authors of (*Bhushan et al., 2020*).

CONCLUSIONS

C1) The first conclusion is that all the analyses proposed in this research give the same optimal treatment, T_{12}, exactly like the elementary method used by the authors of the source data. The second best performing treatment is T_8, also for all efficiency evaluation methods.

C2) The conclusions of such a study are valuable from a scientific point of view. They can become more valuable in a context where the accumulated knowledge acquires new values, relative to the environment in which they were obtained. This means placing them in a Puzzle that tests the researchers' ability to integrate, that is, to unite in a general framework the knowledge obtained through analysis, more precisely to synthesize this knowledge. The beginning can be done by integrating the new knowledge obtained in a GIS database, which has enough facilities to link data of the type obtained in this article with environmental knowledge (geologic and climatic), knowledge of physics, chemistry, biology and theory statistics applicable in all fields.

C3) A consequence of the development of the subject of the article, mentioned in many other articles, is the acute need to find the limits of doses applicable in various treatments so that they become optimal in several respects:

- to ensure the maximum quality parameters;
- not to cause impermissible values of some quality parameters related to the maximum admissible content of substances in fruits, seeds, or other parts of the plant;
- not to generate residues that accumulate over time in the soil, with negative effects.

C4) It is important to continue the experimental studies until the economic and quality consequences of the final products. Without the economic and quality consequences of the crop, it is hard to imagine that farmers would accept the recommendations. Certainly, farmers will want to know how much the price of the final product will increase and what its quality will be when they opt for one of the recommended treatments.

Moreover, the modern farmer may want to know the long-term consequences of applying the recommended treatments.

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NUMERICAL AND ANALYTICAL MODELING OF A NINE–DEGREE-OF-FREEDOM HUMAN–DRIVER BIOMECHANICAL SYSTEM
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MODELAREA NUMERICĂ ȘI ANALITICĂ A SISTEMULUI BIOMECANIC UMAN – CONDUCĂTOR AUTO CU 9 GRADE DE LIBERTATE

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Keywords: *human biomechanical model; nine degrees of freedom (9DOF); mechanical vibrations; mass–spring–damper system; numerical simulation; experimental validation*

ABSTRACT

This paper proposes a human biomechanical model with nine degrees of freedom, developed and validated to simulate the dynamic behaviour of a vehicle driver exposed to mechanical vibrations, particularly during the operation of self-propelled agricultural vehicles such as tractors. The proposed model enables a detailed three-dimensional analysis of the biomechanical response of a virtual anthropometric dummy seated on the vehicle seat and consists of nine anatomical segments: head, neck, trunk, upper arms, forearms, hands, thighs, shanks, and feet. Each segment is represented by a lumped mass located at the centre of gravity of the corresponding anatomical part. Based on this representation, a system of nonlinear differential equations was formulated to describe the dynamic behaviour of the coupled human–vehicle biomechanical system.

The model was numerically implemented and solved using appropriate analytical methods, and simulations were performed under various vibrational excitation conditions characteristic of agricultural vehicles operating in real working environments, with the vibrational impulse defined by the initial conditions. The obtained results are presented graphically, highlighting the distribution and propagation of vibrations throughout the human body structure, as well as the dynamic response of each segment with respect to excitation frequency and amplitude. Within this study, specialized SimulationX software was used to generate graphical representations of the position and velocity amplitude variations of the segments of the nine-degree-of-freedom biomechanical model, the characteristic curves of the mass–spring–damper system associated with each segment, and the distributions of kinetic energy, potential energy, and power losses for each elastic element and damper, analysed at the identified natural frequencies.

REZUMAT

Această lucrare propune un model biomecanic uman cu nouă grade de libertate, dezvoltat și validat pentru a simula comportamentul dinamic al conducătorului auto expus vibrațiilor mecanice, în special în timpul operării vehiculelor agricole autopropulsate de tip tractor. Modelul propus permite o analiză tridimensională detaliată a comportamentului biomecanic al unui manechin antropometric virtual, aflat în poziția de șezut pe scaunul vehiculului, și este compus din nouă segmente anatomice: cap, gât, trunchi, brațe, antebrațe, mâini, coapse, gambe și tălpi, fiecare fiind reprezentat printr-o masă concentrată poziționată în centrul de greutate al segmentului corespunzător. Pe baza acestor date, a fost formulat un sistem de ecuații diferențiale neliniare care descrie comportamentul dinamic al întregului sistem biomecanic uman-vehicul. Modelul a fost implementat numeric și rezolvat cu ajutorul metodelor analitice adecvate, fiind realizată o simulare pentru diferite condiții de excitație vibrațională caracteristice vehiculelor agricole în regim de exploatare reală, iar impulsul vibrator fiind determinat de condițiile inițiale. Rezultatele obținute sunt prezentate sub formă grafică, evidențiind distribuția și propagarea vibrațiilor în structura corpului uman și comportamentul fiecărui segment în raport cu frecvența și amplitudinea excitației. În cadrul acestui studiu, utilizând software-ul specializat Simulation X, au fost generate reprezentări grafice pentru variația amplitudinii poziției și vitezei segmentelor modelului biomecanic cu 9 grade de libertate, curbele caracteristice ale sistemului arc-amortizor aferente fiecărui segment, precum și distribuțiile energiei cinetice, energiei potențiale și pierderilor de putere pentru fiecare element elastic și amortizor, analizate la frecvențele proprii determinate.

INTRODUCTION

In the context of the increasing exposure of vehicle drivers to mechanically induced vibrations, biodynamic modelling of the human body has become essential for assessing driver comfort and health. From the perspective of modelling the human response to vibration, the specialized literature classifies biodynamic models into three main categories: lumped-parameter models, continuous models, and discrete models. Lumped-parameter models, although simplified, are effective for the analysis of vertical vibrations and provide a robust physical and theoretical interpretation of vibration-related phenomena *(Abbas, W., 2010; Wang, W., 2006; Oncescu, T.A., 2020)*. Continuous and discrete models offer higher fidelity, as they are developed based on human anatomy and the realistic distribution of mass and stiffness across body segments *(Olinski, M. 2025; Cicchella, A. 2020; Zhang, Q., et. al, 2011)*. Lumped-parameter models represent the human body using a limited number of discrete masses interconnected by elastic and damping elements. Each of these modelling approaches presents specific advantages and limitations and is selected according to the objectives and complexity of the study.

These models are widely appreciated for their simplicity and computational efficiency, being particularly useful for interpreting experimental data and providing a clear physical and theoretical understanding of vibrational phenomena *(Ding, X., et. al 2023)*. Continuous models treat the human body as a medium with distributed parameters, allowing a detailed description of its mechanical behaviour. Such models exhibit increased fidelity, as they are constructed based on anatomical considerations and realistic mass and stiffness distributions of body segments *(Cheng, Z., et. al, 2024)*. Discrete models offer a compromise between complexity and accuracy by representing the human body as a series of rigid segments connected through joints, thereby capturing the dynamic behaviour of different body parts *(Jie, Y., et. al, 2025)*.

The human body is an extremely complex biomechanical system, whose dynamic behaviour has been extensively studied both in the context of voluntary motion and in interaction with external factors such as mechanical vibrations. In particular, the analysis of normal and pathological gait has served as a starting point for the development of advanced biomechanical models *(Rusu L, et. al, 2009; Tarnita, D., et. al, 2013; Tarnita, D., et. al, 2018)*. These studies have been supported by numerical simulations performed on virtual humanoid mannequins and by biomechanical experiments conducted in specific anatomical planes (sagittal and frontal), using modern data acquisition equipment such as Biometrics systems with wearable sensors *(Tarnita, D., et. al, 2013; Geonea, I., 2017)* or video-based motion capture systems *(Berceanu, C., et al., 2010)*.

In recent decades, research efforts have focused on the development of mathematical models capable of accurately reproducing the biodynamic behaviour of vehicle drivers exposed to vibrations, with the aim of mitigating their adverse effects on health. Consequently, relevant models have been proposed to describe the human response in a seated posture, with or without backrest support, under vertical vibration exposure (). The significance of these studies lies in establishing safe exposure limits, evaluating the sensitivity of the human body to different vibration frequencies, and providing a scientific basis for ergonomic solutions aimed at protecting vehicle operators, particularly in agriculture and transportation.

Prolonged exposure of drivers to mechanical vibrations, especially those transmitted through the vehicle seat, can lead to a range of negative health effects, including muscular fatigue, lower back pain, circulatory disorders, and even structural changes in the spinal column *(Hubinger, L., et al., 2014; Murphy, D., et al. 2019)*.

Beyond classical approaches, recent developments include multiphase models that integrate both rigid body components and soft tissues with viscoelastic properties, enabling a more realistic simulation of the interaction between the driver and the vibrational environment *(Watson, J., et. al 2021)*.

Furthermore, adaptive models have been developed that allow biomechanical parameters to be adjusted according to the driver's posture, as well as external variables such as road surface characteristics or vehicle type *(Liu, Y., et al. 2022)*. These models are particularly valuable for the design of ergonomic seats and suspension systems, offering the potential to reduce the harmful effects of vibrations through personalized, real-time adjustments.

In addition, the integration of machine learning techniques into biomechanical models enables more accurate estimation of biodynamic responses based on experimentally acquired data, thereby facilitating the development of personalized protective solutions *(Gupta, A., et al. 2023; Singh, K.J. et. al 2024; Cunha, B. et. al 2022; Raymond, S.J. et. al, 2022; Barrie, A. et. al 2024; Umer, W. et. al, 2022; Happee, R. et. al 2023)*. This approach opens new perspectives for improving driver safety and comfort, while also contributing to the reduction of absenteeism and health issues associated with long-term vibration exposure.

MATERIALS AND METHODS

Biomechanical modelling of the human body exposed to mechanical vibrations involves the following fundamental steps:

- Segmentation of the human body in order to define distinct anatomical units;
- Determination of the mass, stiffness, and damping properties of each individual segment;
- Discretization of the segments and their interconnection through springs (stiffness elements) and dampers;
- Calculation of stiffness and damping components for the model connections;
- Formulation and solution of the system of differential equations describing the dynamic behavior of the model;
- Numerical determination of segment displacements and velocities;
- Graphical representation of displacements, velocities, and characteristic curves describing the forces in the springs and dampers for each segment of the biomechanical model;
- Graphical representation of the kinetic and potential energy as well as power losses associated with each spring–damper element.

Based on specifications reported in the specialized literature regarding the effects of vibration exposure on the human driver during vehicle operation, its impact on human health, and existing methods for vibration and shock mitigation transmitted from the road–vehicle system to the human body, this study investigates the phenomenon of vertical vibration exposure acting on a driver seated on a conventional vehicle seat with minimal mechanical and biodynamic performance characteristics.

A biomechanical model with nine degrees of freedom was developed and validated for the purpose of conducting static and dynamic tests on a self-propelled agricultural vehicle. This approach enables the investigation of three-dimensional biomechanical behaviour using a virtual anthropometric dummy and allows simulations under various postural configurations, including the seated position on the vehicle seat. The model consists of nine elements representing the human body as lumped masses located at the centres of gravity of the corresponding anatomical components, interconnected by spring–damper assemblies.

The nine segments of the biomechanical model are defined as follows: head (1) with mass m_1, neck (2) with mass m_2, trunk (3) with mass m_3, upper arms (4) with mass m_4, forearms (5) with mass m_5, hands (6) with mass m_6, thighs (7) with mass m_7, shanks (8) with mass m_8, and feet (9) with mass m_9, while the vehicle environment is represented by the seat, with mass m_s.

The nine-degree-of-freedom model is inherently complex, and for the accuracy of the obtained results, the required parameters and mechanical characteristics are summarized in Table 1.

Table 1 *(Abbas W, et. al 2013)*

Mechanical Characteristics of the Nine-Degree-of-Freedom Model

Segment	M_i Initial mass [Kg]	C_S Segmental coefficient	No.	M_S Segment mass [kg]	Stiffness coefficient K [KN/m]	Damping coefficient C [KNs/m]
Head	72.15	0.081	1	5.84	120.00	1.50
Neck		0.04	1	2.89	120.00	1.50
Trunk		0.497	1	35.86	105.00	1.80
Upper arms		0.028	2	4.04	50.00	1.00
Forearms		0.016	2	2.31	50.00	1.00
Hands		0.006	2	0.87	50.00	1.00
Thighs		0.1	2	14.43	50.00	1.10
Shanks (lower legs)		0.0465	2	6.71	50.00	1.00
Feet		0.0145	2	2.09	50.00	1.00
MT Total mass				75.04		

In Table 1, the mechanical characteristics of the proposed model are presented.

The values of the stiffness and damping coefficients were adopted from the specialized literature *(Abbas W, et. al 2013)*, while the masses of the segments constituting the biomechanical model were calculated using Equation (1):

$$Ms=Mi\cdot Cs\cdot No \quad (1)$$

The vibrational impulse is determined by the initial conditions established at the beginning of the study for the analysis of the biomechanical model behavior. In this context, the successive changes occurring in the normal state of the model are described, highlighting the variations of the characteristic displacement amplitude curves as a function of time relative to the equilibrium position, as well as the amplitude plots of the characteristic force curves associated with the springs (k_i) and dampers (c_i).

This approach aims to emphasize the characteristic and defining aspects of the mechanical and biodynamic properties of the components of the proposed model, providing a detailed understanding of how vibrations influence the dynamic behavior of the system.

Figure 1 illustrates the equivalent system of the biomechanical model of the driver in a seated position. The segments constituting the model are denoted as [m_1−m_9+m_{seat}]. Each human body segment is associated with a spring–damper system, characterized by coefficients k_i and c_i, represented beneath each mass. These elements describe both the deformable properties of the body segments and the vibrations transmitted from the floor through the seat to the entire body. The total mass of the model is 75 kg.

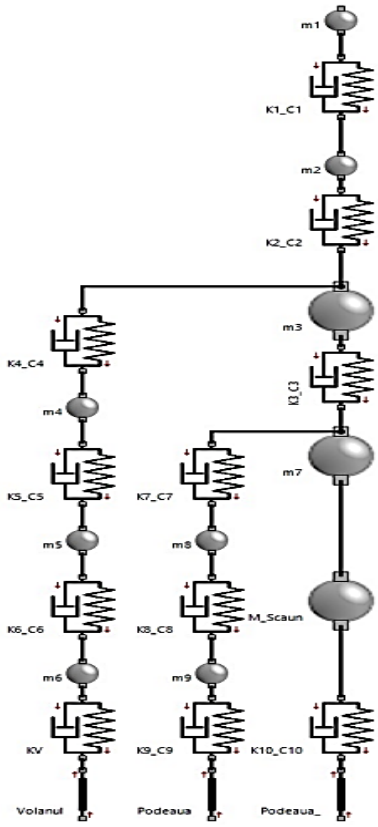


Fig. 1 - Equivalent System of the Nine-Degree-of-Freedom Biomechanical Model

To ensure a clear understanding of the vibration transmissibility phenomenon from the self-propelled agricultural vehicle to the entire human body in the vertical direction, the equivalent system corresponding to the nine-degree-of-freedom biomechanical model was defined.

The equivalent system represents a graphical depiction of the human biomechanical model, in which each body segment is symbolized geometrically and characterized by its defining mechanical properties, namely the mass of each individual segment as well as the corresponding stiffness and damping coefficients.

Using SimulationX software, the system of nine differential equations associated with the proposed model, described by Equations (2–10), was solved both numerically and analytically. This stage enabled a detailed evaluation of the dynamic behavior of the model, facilitating the analysis of vibration transmission and their effects on the simulated biomechanical structures.

$$m_1.\frac{d^2}{dt^2}x_1(t)+c_1.\left(\frac{d}{dt}x_1(t)-\frac{d}{dt}x_2(t)\right)+k_1.(x_1(t)-x_2(t))=0 \text{ - (F1)} \quad (2)$$

$$m_2.\frac{d^2}{dt^2}x_2(t)+c_1.\left(\frac{d}{dt}x_2(t)-\frac{d}{dt}x_1(t)\right)+k_1.(x_2(t)-x_1(t))+c_2.\left(\frac{d}{dt}x_2(t)-\frac{d}{dt}x_3(t)\right)+k_2.(x_2(t)-x_3(t))=0 \text{ (F2)} \quad (3)$$

$$m_3.\frac{d^2}{dt^2}x_3(t)+c_2.\left(\frac{d}{dt}x_3(t)-\frac{d}{dt}x_2(t)\right)+k_2.(x_3(t)-x_2(t))+c_4.\left(\frac{d}{dt}x_3(t)-\frac{d}{dt}x_4(t)\right)+k_4.(x_3(t)-x_4(t))+$$
$$c_3\left(\frac{d}{dt}x_3(t)-\frac{d}{dt}x_7(t)\right)+k_3.(x_3(t)-x_7(t))=0 \quad (4) \text{ (F3)}$$

$$m_4.\frac{d^2}{dt^2}x_4(t)+c_4.\left(\frac{d}{dt}x_4(t)-\frac{d}{dt}x_3(t)\right)+k_4.(x_4(t)-x_3(t))+c_5.\left(\frac{d}{dt}x_4(t)-\frac{d}{dt}x_5(t)\right)+k_5.(x_4(t)-x_5(t))=0 \text{ (F4)} \quad (5)$$

$$m_5.\frac{d^2}{dt^2}x_5(t)+c_5.\left(\frac{d}{dt}x_5(t)-\frac{d}{dt}x_4(t)\right)+k_5.(x_5(t)-x_4(t))+c_6.\left(\frac{d}{dt}x_5(t)-\frac{d}{dt}x_6(t)\right)+k_6.(x_5(t)-x_6(t))=0 \text{ (F5)} \quad (6)$$

$$m_6.\frac{d^2}{dt^2}x_6(t)+c_6.\left(\frac{d}{dt}x_6(t)-\frac{d}{dt}x_5(t)\right)+k_6.(x_6(t)-x_5(t))+c_V.\left(\frac{d}{dt}x_6(t)-\frac{d}{dt}x_V(t)\right)+k_6.(x_6(t)-x_V(t))=0 \text{ (F volan)}$$

$$m_7.\frac{d^2}{dt^2}x_7(t)+c_3.\left(\frac{d}{dt}x_7(t)-\frac{d}{dt}x_3(t)\right)+k_3.(x_7(t)-x_3(t))+c_7.\left(\frac{d}{dt}x_7(t)-\frac{d}{dt}x_8(t)\right)+k_7.(x_7(t)-x_8(t))+$$
$$c_{10}.\left(\frac{d}{dt}x_7(t)-\frac{d}{dt}x_P(t)\right)+k_{10}.(x_7(t)-x_P(t))=0 \quad (7) \text{ (FPodea)} \quad (8)$$

$$m_8.\frac{d^2}{dt^2}x_8(t)+c_7.\left(\frac{d}{dt}x_8(t)-\frac{d}{dt}x_7(t)\right)+k_7.(x_8(t)-x_7(t))+c_8.\left(\frac{d}{dt}x_8(t)-\frac{d}{dt}x_9(t)\right)+k_8.(x_8(t)-x_9(t))=0 \text{(F8)} \quad (9)$$

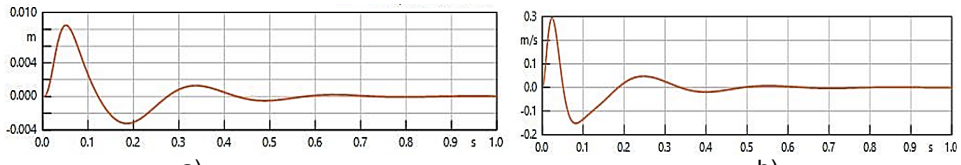
$$m_9.\frac{d^2}{dt^2}x_9(t)+c_8.\left(\frac{d}{dt}x_9(t)-\frac{d}{dt}x_8(t)\right)+k_8.(x_9(t)-x_8(t))+c_9.\left(\frac{d}{dt}x_9(t)-\frac{d}{dt}x_P(t)\right)+k_9.(x_9(t)-x_P(t))=0 \text{ (F9)} \quad (10)$$

RESULTS

SimulationX is an advanced simulation environment developed for the analysis of multi-domain systems and is widely used in mechanical engineering, mechatronics, and biomechanics. This software enables the modeling, simulation, and dynamic analysis of complex systems through an extensive library of predefined components, as well as the capability to define customized differential equations. In the context of biomechanical studies, SimulationX provides robust tools for the construction and simulation of multi-degree-of-freedom models by integrating specific biomechanical parameters (mass, stiffness, damping) and system initial conditions [32].

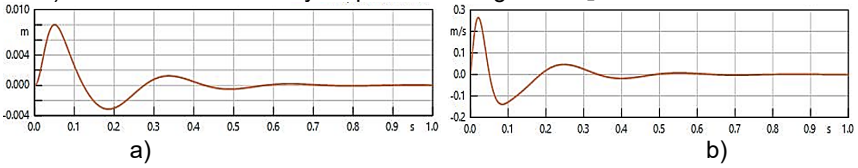
For the analyzed nine-degree-of-freedom biomechanical model, the software enabled the implementation of a set of second-order differential equations associated with each human body segment (x_1 - x_9), as well as with the seat (x_s), which is represented as a spring–damper element.

Upon applying an impulse of 0.0035 m with an initial velocity of 0.2187 m/s, the software generated the characteristic diagrams of displacement variation (a) and velocity amplitude (b) for all degrees of freedom, as presented in Figures 2–11. These diagrams provide an accurate visualization of the dynamic response of each body segment, thereby facilitating the assessment of the biomechanical system behavior under vertical excitation conditions.



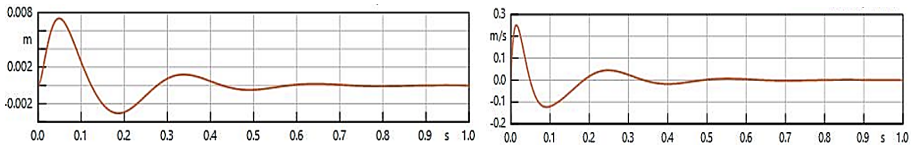
a) b)

Fig. 2 a) Variation of the displacement amplitude from the initial position for segment m_1 (head) as a function of time; b) Variation of the velocity amplitude for segment m_1 as a function of time



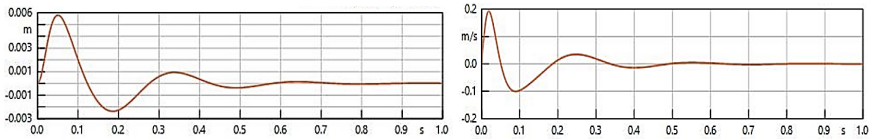
a) b)

Fig. 3 a) Variation of the displacement amplitude from the initial position for segment m_2 (neck) as a function of time; b) Variation of the velocity amplitude for segment m_2 as a function of time



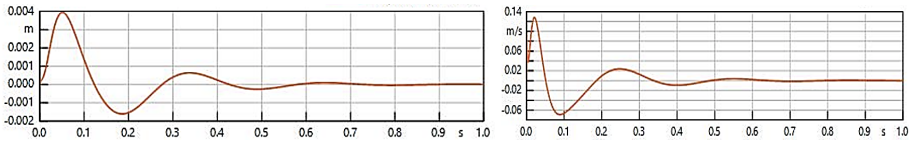
a) b)

Fig. 4 a) Variation of the displacement amplitude from the initial position for segment m_3 (trunk) as a function of time; b) Variation of the velocity amplitude for segment m_3 as a function of time



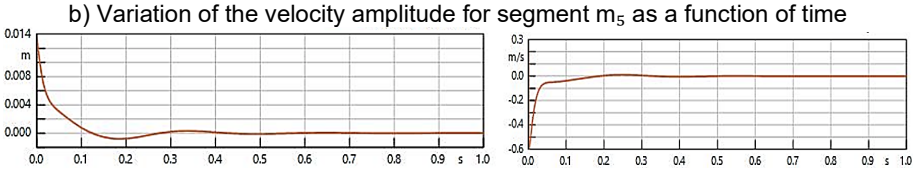
a) b)

Fig. 5 a) Variation of the displacement amplitude from the initial position for segment m_4 (upper arms) as a function of time;
b) Variation of the velocity amplitude for segment m_4 as a function of time



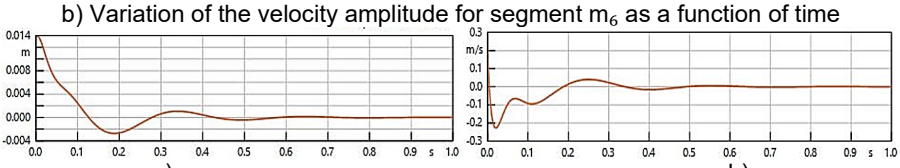
a) b)

Fig. 6 a) Variation of the displacement amplitude from the initial position for segment m_5 (forearms) as a function of time; b) Variation of the velocity amplitude for segment m_5 as a function of time



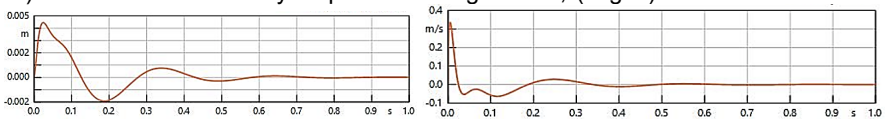
a) b)

Fig. 7 a) Variation of the displacement amplitude from the initial position for segment m_6 (hands) as a function of time; b) Variation of the velocity amplitude for segment m_6 as a function of time



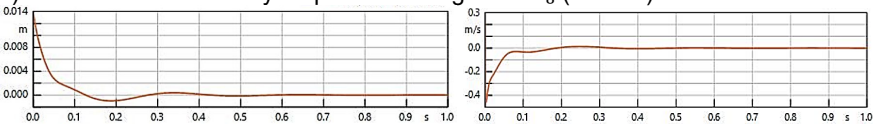
a) b)

Fig. 8 a) Variation of the displacement amplitude from the initial position for segment m_7 (thighs) as a function of time; b) Variation of the velocity amplitude for segment m_7 (thighs) as a function of time



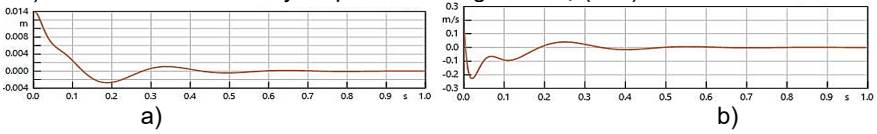
a) b)

Fig. 9 a) Variation of the displacement amplitude from the initial position for segment m_8 (shanks) as a function of time; b) Variation of the velocity amplitude for segment m_8 (shanks) as a function of time



a) b)

Fig. 10 a) Variation of the displacement amplitude from the initial position for segment m_9 (feet) as a function of time; b) Variation of the velocity amplitude for segment m_9 (feet) as a function of time



a) b)

Fig. 11 Variation of the displacement amplitude from the initial position for the seat (m_{seat}) as a function of time; b) Variation of the seat velocity amplitude as a function of time

DISCUSSION

The selection of a nine-degree-of-freedom biomechanical model for vibration analysis was motivated by the need to accurately capture the complex and nonlinear response of the human body to mechanical

vibrations, which is essential for obtaining relevant and applicable results. While simpler models may be adequate for linear systems or for situations where a generalized average response is sufficient, the inherent complexity of human biodynamic behavior—strongly influenced by factors such as vibration direction and individual characteristics (e.g., body mass)—requires the adoption of a more detailed modeling approach.

The nine-degree-of-freedom model enabled a more precise analysis of vibration modes and the dynamic behavior of the human body under the investigated scenario, namely vibrations transmitted through the seat of a self-propelled agricultural vehicle during operation. This level of complexity is crucial to ensure that ergonomic or technological modifications aimed at reducing discomfort and health risks for drivers are properly substantiated. Moreover, the use of such a detailed model ensures that specific characteristics of the human response are captured in a manner that allows the results to be scaled and adapted for different user categories, such as various age groups and genders, without compromising accuracy.

The natural frequencies identified for the nine-degree-of-freedom biomechanical model are 3.29 Hz, 8.66 Hz, and 11.75 Hz. These values correspond to the characteristic natural frequencies at which the model tends to vibrate. Such natural frequencies are fundamental for understanding the dynamic behavior of the system and for assessing the effects of vibration exposure on the human body under different operational conditions.

Within the vibration analysis performed using SimulationX software, the kinetic energy corresponding to each identified frequency was determined for each mass of the biomechanical model segments (m_1-m_9), as well as for the seat mass. This energy-based analysis provides additional insight into the distribution of dynamic loads within the system and supports a deeper interpretation of the biodynamic response of the human body to mechanical vibrations.

These masses represent different components of the human body and the seat, playing a significant role in the dynamic analysis of the system at the identified frequencies. The corresponding graphical representations are presented in Figures 12–20.

Kinetic Energy (f1 = 3.2905 [Hz])

Element	Energy/Power
Sum:	2.3944
m1	0.1827
m2	0.0864
m3	1.0000
m4	0.0683
m5	0.0179
m6	0.0017
m7	0.3289
m8	0.0751
m9	0.0060
M_Scaun	0.6275

Fig. 12 Graphical representation of the kinetic energy calculation at frequency f_1 for each mass of the nine-degree-of-freedom (9DOF) biomechanical model

Kinetic Energy (f2 = 8.6692 [Hz])

Element	Energy/Power
Sum:	1.3954
m1	0.2207
m2	0.0619
m3	0.2679
m4	0.0380
m5	0.0130
m6	0.0013
m7	0.2253
m8	0.1256
m9	0.0117
M_Scaun	0.4299

Fig. 13 Graphical representation of the kinetic energy calculation at frequency f_2 for each mass of the nine-degree-of-freedom (9DOF) biomechanical model

Kinetic Energy (f3 = 11.751 [Hz])

Element	Energy/Power
Sum:	1.8651
m1	1.0000
m2	0.0928
m3	0.4721
m4	0.1227
m5	0.0516
m6	0.0055
m7	0.0297
m8	0.0310
m9	0.0032
M_Scaun	0.0566

Fig. 14 Graphical representation of the kinetic energy calculation at frequency f_3 for each mass of the nine-degree-of-freedom (9DOF) biomechanical model

Furthermore, within the SimulationX software environment, the potential energy and power losses were calculated for each elastic constant (spring) and damper in the system, labeled from c_1 to c_9 and from k_1 to k_9, including the stiffness and damping characteristics of the seat, at the frequencies identified in the analysis.

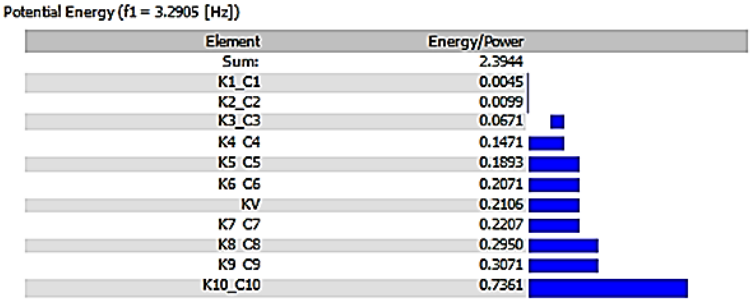


Fig. 15 Graphical representation of the potential energy calculation at frequency f_1 for each elastic constant (spring) and damper of the nine-degree-of-freedom (9DOF) biomechanical model

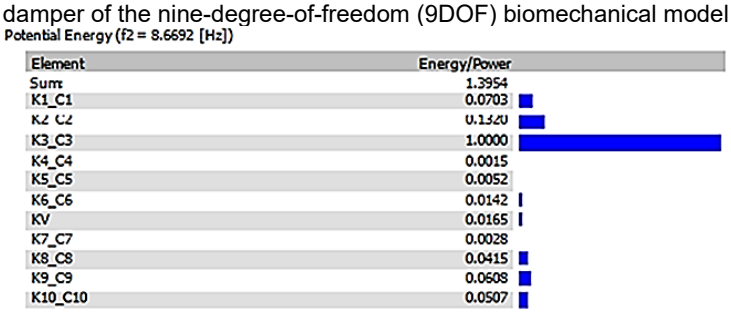


Fig. 16 Graphical representation of the potential energy calculation at frequency f_2 for each elastic constant (spring) and damper of the nine-degree-of-freedom (9DOF) biomechanical model

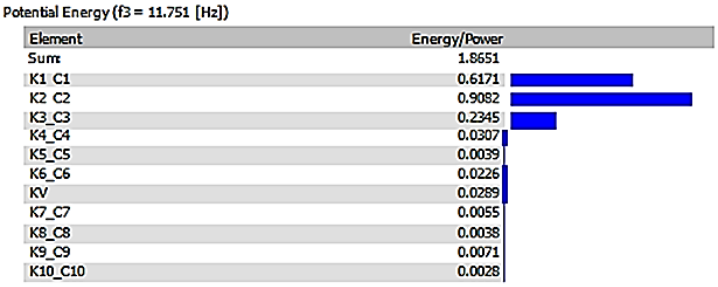


Fig. 17 Graphical representation of the potential energy calculation at frequency f_3 for each elastic constant (spring) and damper of the nine-degree-of-freedom (9DOF) biomechanical model

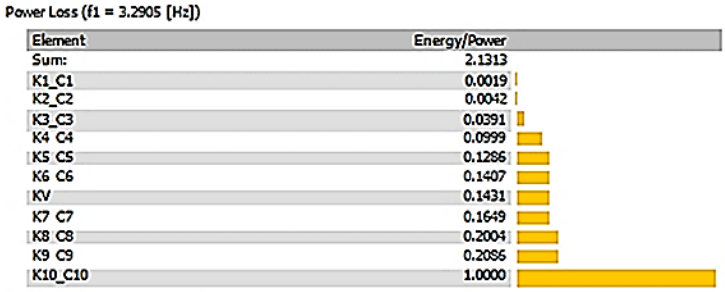


Fig. 18 Graphical representation of the power loss calculation at frequency f_1 for each elastic constant (spring) and damper of the nine-degree-of-freedom (9DOF) biomechanical model

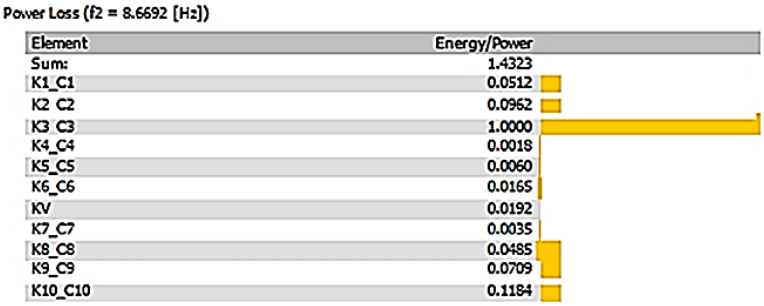


Fig. 19 Graphical representation of the power loss calculation at frequency f_2 for each elastic constant (spring) and damper of the nine-degree-of-freedom (9DOF) biomechanical model

Power Loss (f3 = 11.751 [Hz])

Element	Energy/Power
Sum:	2.2251
K1_C1	0.6794
K2_C2	1.0000
K3_C3	0.3541
K4_C4	0.0540
K5_C5	0.0069
K6_C6	0.0399
KV	0.0509
K7_C7	0.0107
K8_C8	0.0066
K9_C9	0.0126
K10_C10	0.0100

Fig. 20 Graphical representation of the power loss calculation at frequency f_2 for each elastic constant (spring) and damper of the nine-degree-of-freedom (9DOF) biomechanical model

These values were determined for each frequency analyzed within the nine-degree-of-freedom (9DOF) biomechanical model. The potential energy reflects the ability of each elastic element and damper to store energy during oscillatory motion, while the power losses indicate the energy dissipated through damping and friction processes.

The Campbell diagram generated using SimulationX software represents an essential tool in the vibrational analysis of the human biomechanical system with nine degrees of freedom and is presented in Figure 21. It provides a comprehensive visualization of the relationship between the system's natural frequencies (plotted on the ordinate axis, in Hz) and the excitation source rotational speed (plotted on the abscissa axis, in revolutions per minute), enabling rapid identification of potentially harmful resonance conditions that may occur within the operating range of the vehicle.

Based on the graphical representations obtained in the software—concerning displacement, velocity, kinetic energy, potential energy, and power losses for each segment of the biomechanical model and the seat—the Campbell diagram complements the analysis by offering an integrated perspective on the interaction between the system's natural frequencies and the excitation source speed (e.g., the engine of the self-propelled agricultural vehicle).

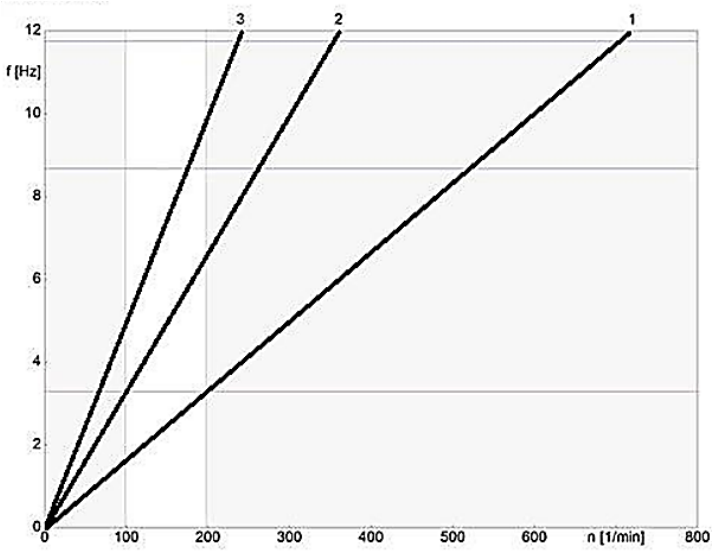


Fig. 21 Campbell Diagram

In the analysed diagram, three main lines (1, 2, and 3) can be distinguished, each corresponding to a previously identified natural frequency: Line 1 corresponds to the natural frequency of 3.29 Hz, Line 2 corresponds to 8.66 Hz, and Line 3 is associated with the frequency of 11.75 Hz.

The slope of each branch expresses the rate of increase between frequency and rotational speed. The intersections of these branches with the typical operating ranges of the agricultural machinery provide important indications of critical resonance zones, in which the amplitude of vibrations transmitted to the human body may become dangerously high.

Line 1, the lowest in the diagram, indicates a high risk of resonance in the low rotational speed range, characteristic of idling or slow manoeuvring—operating conditions in which exposure is prolonged and continuous.

Line 2 intersects the medium rotational speed range, frequently used during normal agricultural field operation, suggesting a potential amplification of vibration transmission to the lumbar and pelvic regions.

Line 3 signals risks in the upper rotational speed range, which may affect drivers during sudden acceleration or under high load conditions, particularly influencing the thoracic region and the head, depending on the posture and configuration of the modelled segments.

The integration of this diagram into the comprehensive analysis of the biomechanical response adds significant analytical depth, enabling the correlation of energetic data (kinetic and potential energy) with critical mechanical operating zones of the self-propelled agricultural vehicle–seat–driver system. In particular, this graphical tool provides an objective basis for optimizing the dynamic characteristics of the seat by shifting the system's natural frequencies outside hazardous rotational speed ranges.

CONCLUSIONS

Following the numerical and analytical modelling of the nine-degree-of-freedom human biomechanical system specific to a seated vehicle driver, it was demonstrated that the use of a complex and detailed model is essential for accurately capturing the dynamic behaviour of the human body subjected to vertical vibrations. The adoption of this modelling approach enabled a differentiated analysis of individual body segments and their interaction with the vehicle seat, revealing a vibrational structure characterized by three dominant natural frequencies—3.29 Hz, 8.66 Hz, and 11.75 Hz—which are associated in the specialized literature with increased discomfort and potential musculoskeletal disorders.

The present research proposes an integrated numerical and analytical approach to the biomechanical modelling of the vehicle driver, employing a complex nine-degree-of-freedom model designed to faithfully reproduce the biodynamic behaviour of the human body under realistic vibration exposure conditions. By using SimulationX software, the characteristic diagrams of displacement, velocity, kinetic energy, potential energy, and power losses were generated and thoroughly analysed for each system component, thus providing a detailed insight into how vibrations affect different body segments as well as the vehicle seat.

The identification of the system's natural frequencies, correlated with rotational speed values through the Campbell diagram, enabled the determination of critical resonance zones and significantly contributed to understanding the energy distribution within the system as a function of operating regime.

From a prospective perspective, the integration of machine learning methods at this stage enables the personalization of protective and ergonomic solutions tailored to different user typologies, further emphasizing the applied nature of the research. This approach provides a solid framework for optimizing the design of vibration mitigation systems in vehicles, while also offering clear directions for improving comfort, safety, and occupational health for agricultural operators, with strong potential for extension to other professional categories exposed to occupational vibrations.

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HOW CORN CROP ENTOMOFAUNA CHANGES OVER TIME: CENTRAL MOLDOVA (ROMANIA)
/
EVOLUȚIA ENTOMOFAUNEI DĂUNĂTOARE CULTURILOR DE PORUMB: CENTRUL MOLDOVEI (ROMÂNIA)

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Keywords: *corn, pests, growing season, development*

ABSTRACT

Pests are a considerable limiting factor in terms of corn cultivation. Research conducted in the central area of Moldova showed that the harmful entomofauna was composed of 16 species, which sum up, on average, in the period 2002-2011 - 288.2 sp./m^2, in the period 2012-2020 – 1832.2 sp./m^2, and in the period 2021-2024 - 3773 sp./m^2. The abundance of harmful species was high in the period 2002-2011, recording the highest values, of 49.3%, in the phase of seed germination, emergence and formation of 3-5 leaves. In the periods 2012-2020 and 2021-2024, the highest values of abundance were recorded during the panicle and ear emergence period, representing 79.9% and 58.7% of the total catches, respectively. Due to the large number of species, but also the number of specimens, the Coleoptera order had the maximum share, recording values of 40% to 92%. The share of specimens collected from the Lepidoptera Order increased greatly, especially in the last analyzed period, 2021-2024, when the density of the four identified species increased greatly, representing 60% of the total specimens. Following this research, it can be appreciated that the key pests of corn during the crop's vegetation period for the area of influence of ARDS Secuieni are: Tanymecus dilaticollis Gyll., Opatrum sabulosum L., Ostrinia nubilalis Hbn., Diabrotica virgifera virgifera Le Conte and Helicoverpa armigera Hbn.

REZUMAT

Dăunătorii constituie un factor limitativ considerabil în ceea ce privește cultura porumbului. Cercetările efectuate în zona centrală a Moldovei au arătat că entomofauna dăunătoare a fost alcătuită din 16 specii, care au totalizat, în medie, în perioada 2002-2011 - 288.2 exp./mp, în perioada 2012-2020 – 1832.2 exp./mp, iar în perioada 2021-2024 - 3773 exp./mp. Abundența speciilor dăunătoare a fost ridicată în perioada 2002-2011, înregistrând cele mai ridicate valori, de 49,3%, în faza de germinare a semințelor, răsărire și formare a 3-5 frunze. În perioadele 2012-2020 și 2021-2024, cele ridicate valori ale abundenței speciilor, s-a înregistrat în perioada de apariție a paniculului și a știuletelui, reprezentând 79,9% respectiv 58,7% din totalul capturilor. Prin numărul mare de specii, dar și prin numărul de exemplare, ordinul Coleoptera a deținut ponderea maximă, înregistrând valori de 40% până la 92%. Ponderea exemplarelor colectate din Ordinul Lepidoptera a crescut foarte mult, în special în ultima perioada analizată, 2021-2024, când densitatea cele patru specii identificate a crescut mult, reprezentând 60% din totalul exemplarelor. În urma acestor cercetări, se poate aprecia că dăunătorii cheie ai culturii de porumb, în perioada de vegetație a culturii pentru zona de influență a SCDA Secuieni sunt: Tanymecus dilaticollis Gyll., Opatrum sabulosum L., Ostrinia nubilalis Hbn., Diabrotica virgifera virgifera Le Conte și Helicoverpa armigera Hbn.

INTRODUCTION

Knowledge of harmful organisms affecting agricultural crops has always been an important tool for agricultural practice, contributing to the establishment of crop protection measures and, consequently, to limiting damage (Badiu, A.F. et al., 2019; Dudoiu, R., et al. 2018; Baicu, T., and Săvescu, A., 1986). Identifying pests and a thorough understanding of their attack methods and crop protection measures against pest attacks are essential for all specialists to act in a timely manner and reduce the damage caused by insects (Trotuș, E., et al., 2021).

Monitoring corn crops ensures that plants successfully overcome pest attacks, which are common during the most vulnerable phenological stages, namely from seed germination to the appearance of 4-5 leaves, and from flowering to grain filling (Trotuș, E., et al., 2017; 2022; Săpunaru, T., et al., 1995). The dynamics of insect populations are influenced by the plant's developmental stage and the climatic conditions in the region (Chiriloaie-Palade, A., et al., 2024; Rantes, A., 2024).

Concerns about the knowledge of insect species in corn crops are current, and this paper represents a continuation of previous research aimed at supplementing existing knowledge in the specialised literature with new data regarding the ecological parameters of the pest species inventoried between 2002 and 2024.

MATERIALS AND METHODS

Research on identifying the harmful entomofauna of agricultural crops in the western part of the Central Moldavian Plateau began in 2002 and has continued uninterrupted to the present day, covering a period of 23 years.

The observations, notes, and determinations included the following activities:

- Ground determinations were made from the plant emergence phase until the formation of 6-8 leaves, using a 25 × 25 cm metric frame, with 16 samples taken along each diagonal of the 1-hectare plots;
- captures using an entomological net (by sweeping), carried out from the stem growth and elongation phase until the panicles or ears, at 10-day intervals;
- Collection of entomofauna using Barber pitfall traps throughout the growing season.

The collected entomofauna was analysed in the laboratory using a binocular microscope, identified to the species and order level, and systematically recorded in the observation register.

Furthermore, the following indicators were calculated:

- The density of harmful species per square meter or per plant, at different stages of crop development, as well as throughout the entire growing season;
- Representative ecological parameters by abundance (A), dominance (D), constancy (C), and ecological significance index (W).

Abundance (A) represents the total number of individuals of a species captured from a specific location on a specific date. Based on the value of this indicator, the other indicators are calculated.

Dominance (D) shows the percentage of participation of each species in the catch. It expresses the relationship between the population size of a species and the sum of the individuals of the other associated species.

This indicator is calculated using the formula: DA = (NA * 100) / N1 NA = the total number of individuals of species A;

N1 = the total number of individuals of all collected species.

Dominance classes include species whose percentage of distribution falls within the following values:

- D1 – supercooled species – distribution percentage P<1.1%;
- D2 – receding species P = 1.2 - 2.0%;
- D3 – subdominant species P = 2.1-5.0%;
- D4 – dominant species P=5.1-10.0%;
- D5 – eudominant species P > 10.1%.

Constancy (C) expresses the continuity of a species' presence in the analysed biotope. This characteristic is a structural indicator because it represents the proportion of a species' participation in the formation of the biocenosis structure. The higher the indicator value, the better adapted the respective species is to the conditions offered by the biotope.

Constancy is calculated using the mathematical formula: CA = (number of occurrences of A / total number of occurrences) x 100 CA – constancy of species A;

nPA – the number of samples in which species A is found;

NP – the total number of samples examined.

Depending on the value of this indicator, species are distributed into the following classes:

- C1 – accidental species (1-25%);
- C2 – accessory species (25.1-50%);
- C3 – constant species (50.1-75%);

- C4 – euconstant species (75.1-100%).

The ecological significance index (W) represents the relationship between the structural indicator (C) and the productive indicator (D).

The ecological significance index is calculated using the formula: WA = (CA * DA * 100) / 10000, where WA = the ecological significance index of species A; CA = constancy of species A; DA = dominance of species A;

Based on the values obtained, the species are divided into the following classes:

- W1 – values below 1% - accidental species class;
- W2 – with values between 1.1-5.0% - accessory species class;
- W3 – with values ranging from over 5.1-10.0% - the characteristic species class, (Buburuz, 2013)

RESULTS

The ecological conditions in the Centre of Moldova were favourable for the appearance, development, and attack of harmful insects that affected corn crops throughout the entire growing season, from seed germination until plant harvesting.

Research conducted between 2002 and 2011 identified the presence of 15 insect species harmful to the corn crop. The highest proportions of the inventoried species were recorded for *Ostrinia nubilalis* Hbn., of 41%, followed by *Tanymecus dilaticollis* Gyll. of 12% and *Harpalus distinguendus* Duff. of 10%. The lowest proportions belonged to the species *Helicoverpa armigera* Hbn., *Amathes c-nigrum* L., and *Lethrus apterus* Laxmann, with 1% (Figure 1).

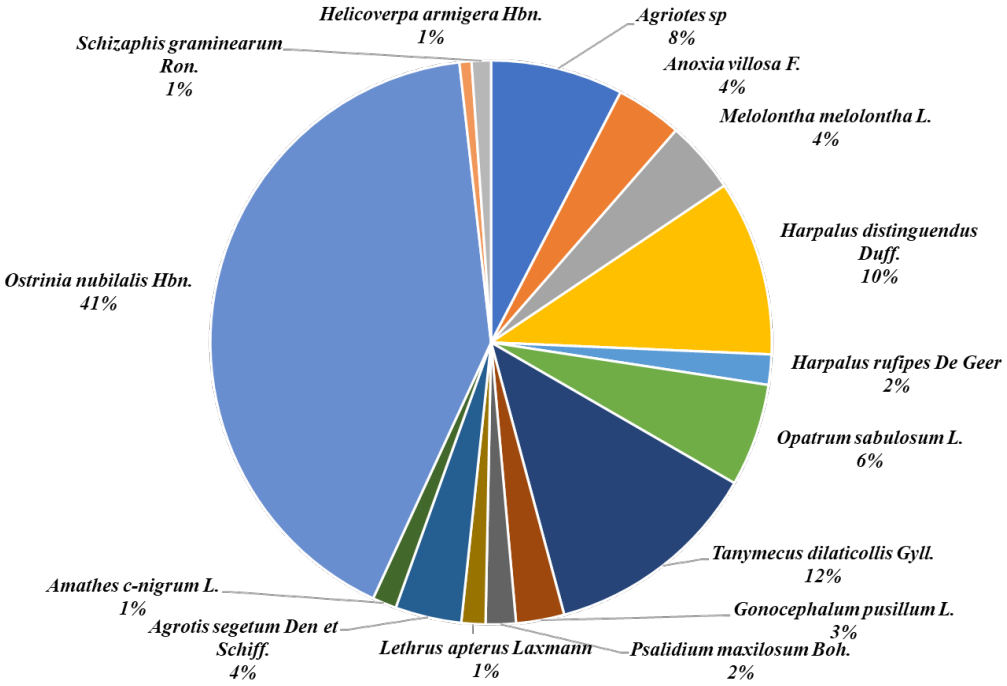

Fig. 1. The share of the harmful insect fauna of corn crops, Secuieni-Neamț (2002-2011)

Regarding the evolution of the entomofauna in corn crops in the eastern part of the country during the period 2012-2020, it was observed that, in addition to the 15 identified species, another species, *Diabrotica virgifera virgifera* Le Conte, was added, which spread with a very high abundance, leading to increases in the average density of insect populations. The highest number of specimens and the highest proportion belonged to the species *Diabrotica virgifera virgifera* Le Conte, accounting for 84% of the total recorded specimens, followed by the species *Ostrinia nubilalis* Hbn with 6%. Similar results were published by Tărău A.D. et al (2023) and Rashev S. et al. (2024), who found that *Diabrotica* populations have increased in recent years in the centre of the country, and in Bulgaria, while Trotuș E. et al. (2018) note the species abundance in the Moldova region and its intense flight.

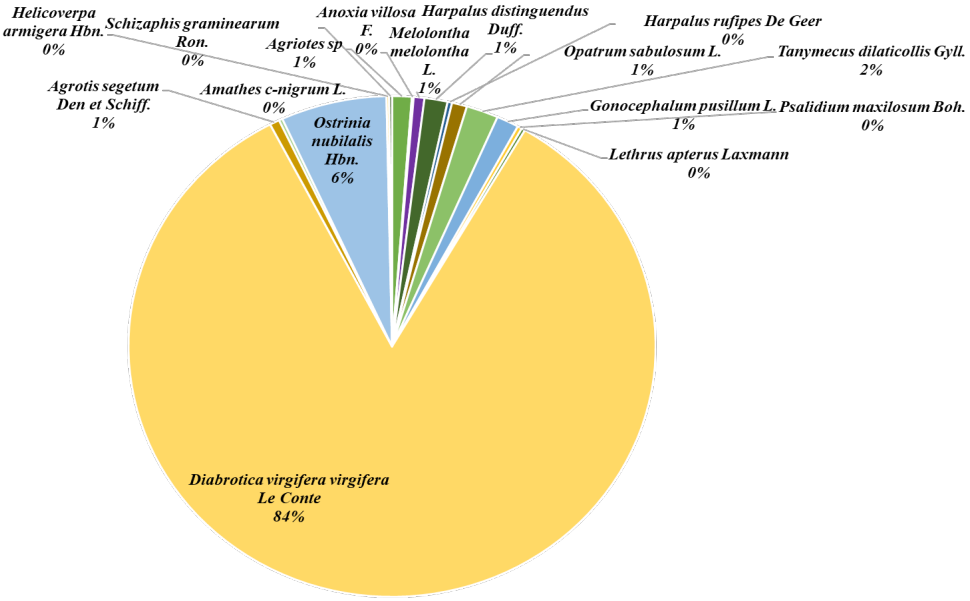

Fig. 2. The share of the harmful insect fauna of corn crops, Secuieni-Neamț (2012-2020)

Over the past four years, the structure of the harmful entomofauna in corn crops has not changed in terms of the number of species. However, we observe the share of the specimens number increased for the species *Diabrotica virgifera virgifera* Le Conte (27%), *Ostrinia nubilalis* Hbn. (28%), *Helicoverpa armigera* Hbn. (26%), *Amathes c-nigrum* L. (5%), and *Harpalus rupifes* Degeer (5%) (Amargioalei, R.G., et al., 2024; Pintilie, P.L., et al. 2024; Georggescu, E., et al., 2025).

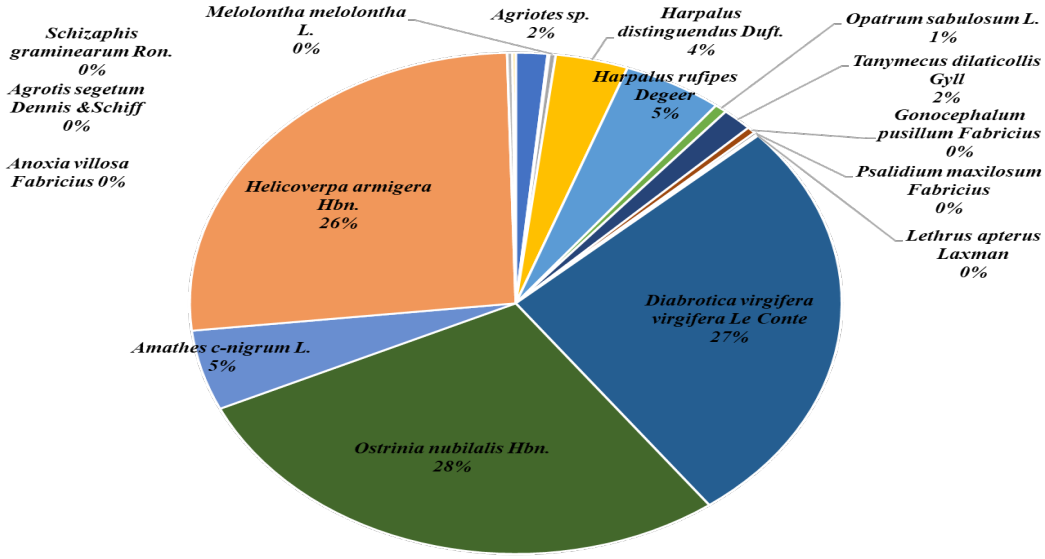

Fig. 3. The share of the harmful insect fauna of corn crops, Secuieni-Neamţ (2021-2024)

Analysing the proportion of systematic orders by number of species, we find that the order Coleoptera recorded the highest proportions, at 66%, totalling 10 species, followed by the order Lepidoptera, with 27% and four species, while the smallest proportion belonged to the order Homoptera, at 7% (one species). Based on the number of specimens, it can be observed that the order Coleoptera had the most collected specimens, 149 specimens, representing 52% of the total captured specimens, followed by the order Lepidoptera, with 137 specimens, representing 47%, and Homoptera with 3.2 colonies, representing 1% (Figure 4).

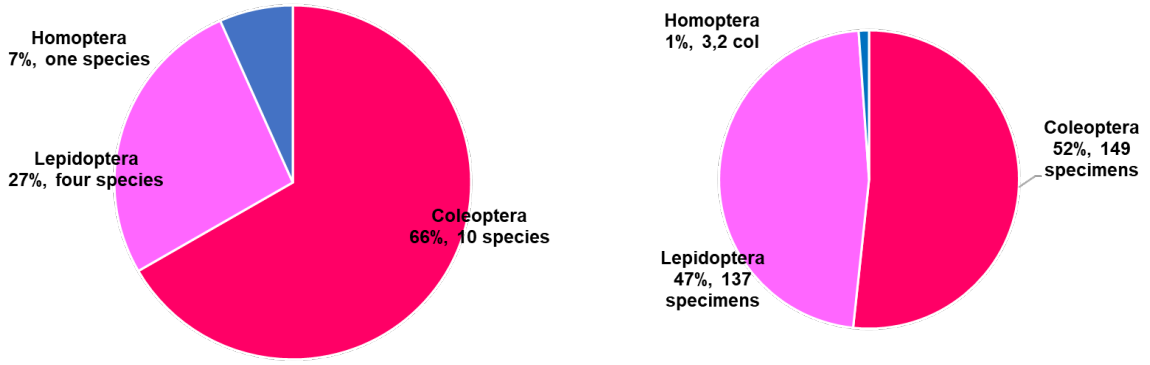

Fig. 4 The share of systematic orders by number of species and number of specimens, Secuieni-Neamț (2002-2010)

Between 2011 and 2020, it was observed that in terms of the number of identified species and specimens, the order Coleoptera held the largest share, accounting for 69% (11 species) and 92% (1692 specimens), respectively, followed by the order Lepidoptera, with 25% (four species) and 7% (137 specimens) (Figure 5).

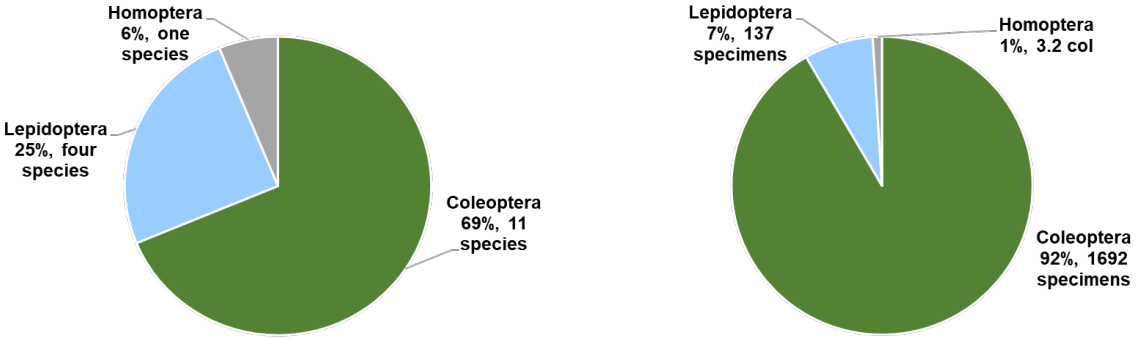

Fig. 5 The share of systematic orders by number of species and number of specimens, Secuieni-Neamț (2011-2020)

For the period 2021-2024, the proportion of systematic orders by the number of identified species remained similar to that in the period 2012-2020. There was a notable increase in the number of collected specimens belonging to the order Lepidoptera, which accounted for 60% and totalled 2262 specimens, followed by the order Coleoptera with 40% and 1505 specimens (Figure 6).

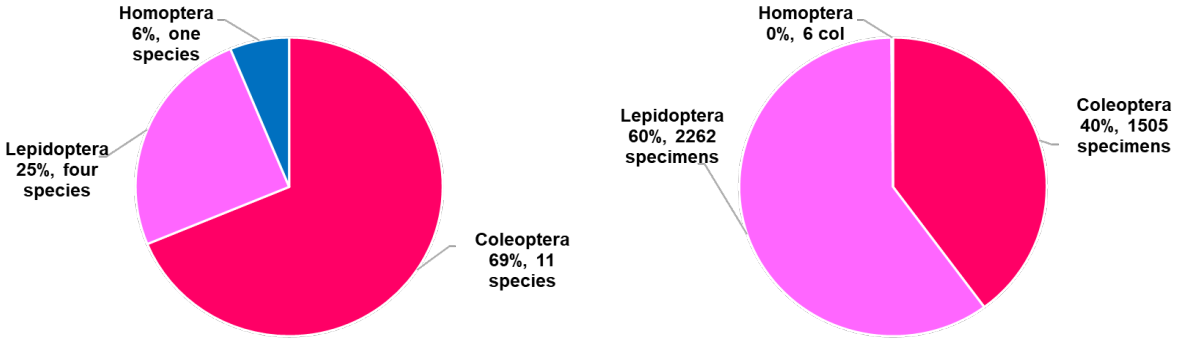

Fig. 6 The share of systematic orders by number of species and number of specimens, Secuieni-Neamț (2021-2024)

Between 2002 and 2010, the average density of the inventoried species at each determination point was correlated with the phenological development stages of corn plants, and it was found that the highest average number of insects, representing 49.3%, was recorded in the germination-emergence-first 3-5 leaf formation stages, while the lowest, representing 9% of the total collected entomofauna, was recorded in the stem elongation and 6-9 leaf formation stages. The remaining phenophases, the appearance of the tassel

and silk, and grain filling and maturation, accounted for 18.3%, representing 52.7 specimens, and 23.4%, totalling 67.5 specimens (Figure 7).

We thus observe that the most vulnerable period for the corn crop between 2002 and 2010 was from sowing until the formation of 5 leaves, when the young plants needed increased protection against soil pests, and this protection was provided by chemical seed treatment with systemic insecticides (Georgescu, E., et al., 2014).

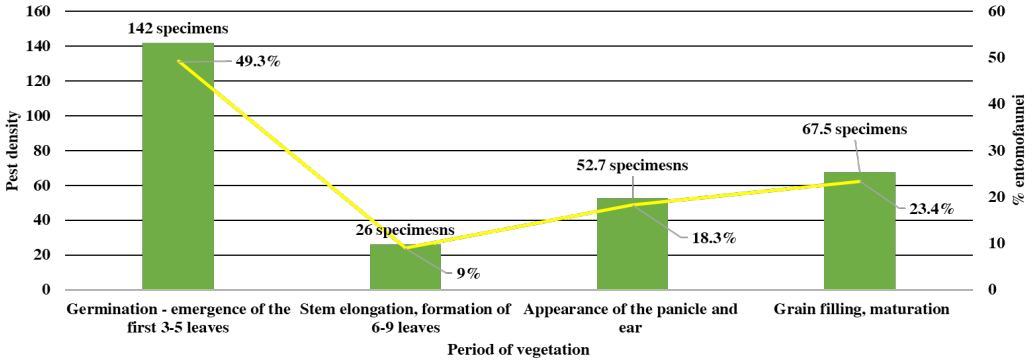

Fig. 7. The share of harmful entomofauna on the phenological phases of corn, Secuieni – Neamț (2002 - 2010)

For the period 2011-2020, it was found that the highest average number of insects, representing 79.9% (1458.2 specimens), was recorded in the heading – silking – grain formation on the cob phenophases (BBCH: 40 - 63), while the lowest, representing 2.8% (51 specimens) of the total collected entomofauna, was recorded in the stem elongation and 6-9 leaf formation phenophases (Figure 8).

Between seed germination and the emergence of the first 3-5 leaves, the proportion of entomofauna was 5.9%, representing 108 specimens. However, this remains a vulnerable period for the corn crop due to soil pest populations consisting of species like *Agriotes* spp., *Tanymecus*, and *Opatrum sabulosum*, which pose a serious problem for corn crops in the Moldavian region (Trotus, E., et al., 2019; Pintilie, P.L., et al., 2023).

An increase in the proportion of captured specimens was observed compared to the previous period during the grain filling and ripening phase, when the proportion was 11.3%, representing 207 specimens. This increase occurred following the registration of the *Diabrotica* species in the Moldova region, which developed numerous adult populations that persist in the corn crop from the appearance of the tassel and ear until grain maturation.

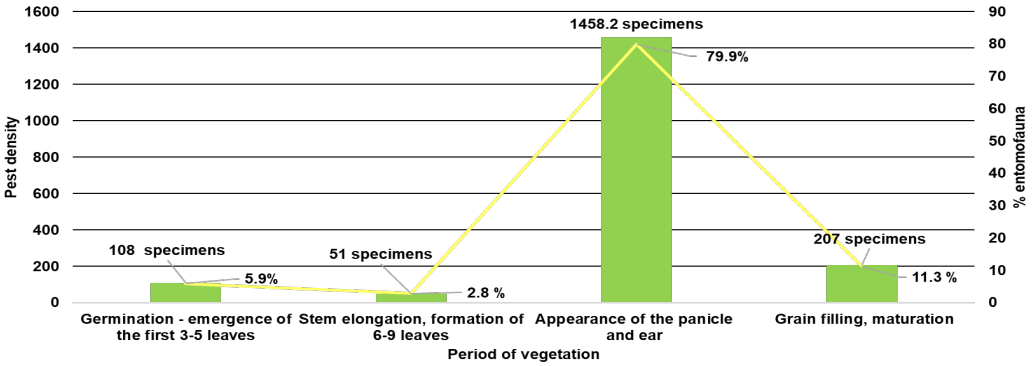

Fig. 8. The share of harmful entomofauna on the phenological phases of corn, Secuieni – Neamț (2011 - 2020)

For the period 2021-2024, by relating the average density of harmful insects to the phenological stages of corn plant development, it was found that the highest density, of 2214 specimens, representing 58.7% of the total entomofauna, was recorded during the period between panicle emergence and ear formation, followed by the interval between grain filling and maturity with 27.6%, representing 1043 specimens. These high values were recorded due to the increase in lepidopteran populations (*Ostrinia nubilalis* Hbn., *Helicoverpa armigera* Hbn., and *Amates-c nigrum* L.) along with the *Diabrotica* species, and the second part of the corn crop's growing season can be compromised by pest attacks that affect the harvest both qualitatively and quantitatively (Figure 9).

Although 6.4% of the total entomofauna, totalling 241 specimens, was recorded during the germination-emergence-first 3-5 leaf formation period, this interval remains vulnerable to soil pest

populations, especially since systemic insecticides for corn seed treatment are no longer approved (Figure 9) (Zaharia, R., et al., 2023).

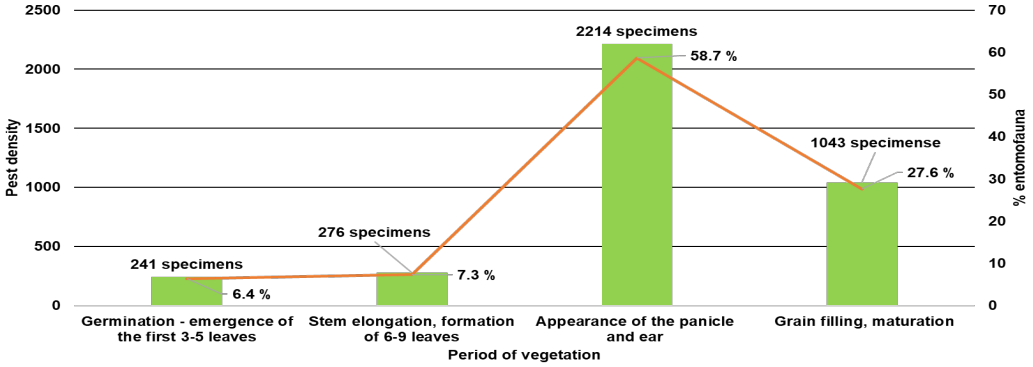

Fig. 9. The share of harmful entomofauna on the phenological phases of corn, Secuieni – Neamț (2021 - 2024)

For the harmful insects collected in corn crops during the period 2012 – 2020, the ecological parameters represented by: Abundance, Dominance, Constancy, and the Ecological Significance Index were calculated, and it was found that:

- the abundance values (A) ranged between 2.0 specimens/m^2 and 119 specimens/m^2. The highest values were recorded for the species: *Ostrinia nubilalis* Hbn. (119 specimens/m^2), *Tanymecus dilaticollis* Gyll. (36 specimens/m^2), *Harpalus distinguendus* Duff. (29 specimens/m^2), while the lowest were recorded for the species: *Anoxia villosa* F. (2 specimens/m^2), *Helicoverpa armigera* Hbn. (2 specimens/m^2) (Table 1);

- dominance (D), an index representing the percentage of participation of each species in the catch, ranged between 0.7% (*Helicoverpa armigera* Hbn.) and 41.3% (*Ostrinia nubilalis* Hbn.), and constancy (C) had values between 0.3% and 50% (Table 1);

- based on the values of the ecological significance index (W), which ranged between 0.0% (*Helicoverpa armigera* Hbn., *Schizaphis graminearum* Ron.) and 20.6% (*Diabrotica virgifera virgifera* Le Conte).

Table 1

Ecological parameters of the entomofauna collected in corn crops, Secuieni-Neamț (2002 - 2011)

No.	Species	A	D	C	W
1.	*Agriotes sp*	22	7.6	31.3	2.39
2.	*Anoxia villosa* F.	11	3.8	31.3	1.19
3.	*Melolontha melolontha* L.	12	4.2	18.8	0.78
4.	*Harpalus distinguendus* Duff.	29	10.1	75.0	7.55
5.	*Harpalus rufipes* De Geer	5	1.7	31.3	0.54
6.	*Opatrum sabulosum* L.	17	5.9	37.5	2.21
7.	*Tanymecus dilaticollis* Gyll.	36	12.5	43.8	5.46
8.	*Gonocephalum pusillum* L.	8	2.8	37.5	1.04
9.	*Psalidium maxilosum* Boh.	5	1.7	4.0	0.07
10.	*Lethrus apterus* Laxmann	4	1.4	18.8	0.26
11.	*Agrotis segetum* Den et Schiff.	11	3.8	31.3	1.19
12.	*Amathes c-nigrum* L.	4	1.4	18.8	0.26
13.	*Ostrinia nubilalis* Hbn.	119	41.3	50.0	20.65
14.	*Helicoverpa armigera* Hbn.	2	0.7	0.3	0.00
15.	*Schizaphis graminearum* Ron.	3.2	1.1	0.6	0.01
Total	***15 species***	**288.2**	**x**	**x**	**x**

The inventoried species were classified into three classes, as follows (Table 2):

- nine species were classified in class W1, which includes accidental species with an ecological significance index less than 1.0%;
- four species (*Agriotes sp., Anoxia villosa* F., *Opatrum sabulosum* L., *Agrotis segetum* Den et Schiff) were classified in class W2, which includes accessory species with an ecological significance index ranging from 1.2% to 2.4%, thus falling within the 1.1% to 5.0% range defined by the class.
- three species, *Tanymecus dilaticollis* Gyll., *Harpalus distinguendus* Duft., and *Ostrinia nubilalis* Hbn., with an ecological significance index above 5.1%, were classified in class W3, which includes characteristic species (Table 2).

Table 2

Classification of pest species by ecological significance index, Secuieni - Neamț (2002-2011)

No.	W1	W2	W3
	Sp. Accidental W < 1.0 %	**Sp. Accessories W = 1.1 – 5.0 %**	**Sp. Characteristics W > 5.1 %**
1.	*Gonocephalum pusillum* F.	*Agriotes* sp *Anoxia villosa* F. *Opatrum sabulosum* L. *Agrotis segetum* Den et Schiff	*Tanymecus dilaticollis* Gyll *Harpalus distinguendus* Duft. *Ostrinia nubilalis* Hbn.
2.	*Melolontha melolontha* L.		
3.	*Agrotis segetum* Den et Schiff.		
4.	*Harpalus rufipes* Deg.		
5.	*Psalidium maxilosum* F.		
6.	*Lethrus apterus* L.		
7.	*Amathes c-nigrum* L.		
8.	*Schizaphis graminum* Ron.		
9.	*Helicoverpa armigera* Hbn.		
TOTAL	**nine species**	**four species**	**three species**

For the harmful insects collected in corn crops during the period 2012 – 2020, ecological parameters were calculated, and it was found that:

- abundance values (A) ranged between 2.0 specimens/m² and 1538 specimens/m². The highest values were recorded for the species: *Diabrotica virgifera virgifera* Le Conte (1538 specimens/m²), *Ostrinia nubilalis* Hbn. (119 specimens/m²), *Tanymecus dilaticollis* Gyll. (36 specimens/m²), *Harpalus distinguendus* Duff. (26 individuals/m²), while the lowest were recorded for the species: *Anoxia villosa* F. (2 specimens/m²), *Helicoverpa armigera* Hbn. (3 specimens/m²) (Table 3);
- dominance (D), an index representing the percentage of participation of each species in the catch, ranged between 0.11% (*Anoxia villosa* F., *Helicoverpa armigera* Hbn.) and 83.9% (*Diabrotica virgifera virgifera* Le Conte), and constancy (C) had values between 11.8% and 52.9% (Table 3);
- based on the values of the ecological significance index (W), which ranged between 0.01% (*Anoxia villosa* F.) and 47.24% (*Diabrotica virgifera virgifera* Le Conte).

Table 3

Ecological parameters of the entomofauna collected in corn crops, Secuieni-Neamț (2012 - 2020)

No.	Specia	A	D	C	W
1.	*Ostrinia nubilalis* Hbn.	119	6,5	47.1	3.1
2.	*Tanymecus dilaticollis* Gyll	36	2.0	29.4	0.6
3.	*Harpalus distinguendus* Duft	26	1.4	70.6	1.0
4.	*Gonocephalum pusillum* F.	25	1.4	41.2	0.6
5.	*Agriotes* sp.	22	1.2	29.4	0.4
6.	*Opatrum sabulosum* L.	17	0.9	35.3	0.3
7.	*Melolontha melolontha* L.	12	0.7	17.6	0.1
8.	*Agrotis segetum* Den et Schiff	11	0.6	29.4	0.2
9.	*Harpalus rufipes* Deg.	5	0.3	29.4	0.1
10.	*Psalidium maxilosum* F.	5	0.3	23.5	0.1
11.	*Lethrus apterus* L.	4	0.2	17.6	0.0
12.	*Amathes c-nigrum* L.	4	0.2	17.6	0.0
13.	*Schizaphis graminum* Ron.	3.2	0.2	23.5	0.0
14.	*Helicoverpa armigera* Hbn.	3	0.2	17.6	0.0
0.015.	*Anoxia villosa* F.	2	0.1	11.8	0.0
16.	*Diabrotica virgifera virgifera* Le Conte.	1538	83.9	52.9	44.4
Total	**16 species**	**1832.2**	**x**	**x**	**x**

The inventoried species were classified into three classes as follows (Table 4):

- 14 species were classified in class W1. which includes accidental species with an ecological significance index less than 1.0%;
- one species (*Ostrinia nubilalis* Hbn.) was classified in class W2, which includes accessory species with an ecological significance index of 3.25%, thus falling within the range of 1.1% to 5.0% as defined by the class;
- one species, *Diabrotica virgifera virgifera* Le Conte, with an ecological significance index of 47.24%, was classified in class W3, which includes characteristic species (Table 4).

Table 4

Classification of Pest Species by Ecological Significance Index, Secuieni - Neamț (2012-2020)

No.	W1	W2	W3
	Sp. Accidental W < 1.0 %	**Sp. Accessories W = 1.1 – 5.0 %**	**Sp. Characteristics W > 5.1 %**
1.	*Tanymecus dilaticollis* Gyll	*Ostrinia nubilalis* Hbn.	*Diabrotica virgifera virgifera* Le Conte.
2.	*Harpalus distinguendus* Duft.		
3.	*Gonocephalum pusillum* F.		
4.	*Agriotes sp.*		
5.	*Opatrum sabulosum* L.		
6.	*Melolontha melolontha* L.		
7.	*Agrotis segetum* Den et Schiff.		
8.	*Harpalus rufipes* Deg.		
9.	*Psalidium maxilosum* F.		
10.	*Lethrus apterus* L.		
11.	*Amathes c-nigrum* L.		
12.	*Schizaphis graminum* Ron.		
13.	*Helicoverpa armigera* Hbn.		
14.	*Anoxia villosa* F.		
TOTAL	**14 species**	**one species**	**one species**

For the period 2021-2024, the ecological parameters calculated for the species collected from corn crops revealed the following:

- abundance values (A) ranged between 3.0 specimens/m² and 1064 specimens/m². The highest values were recorded for the following species: *Diabrotica virgifera virgifera* Le Conte (1002 specimens/m²), *Ostrinia nubilalis* Hbn. (1064 specimens/m²), *Helicoverpa armigera* Hbn. (993 specimens/m²), and the lowest for the species: *Anoxia villosa* Fabricius (3 specimens/m²), *Lethrus apterus* Laxman (4 specimens/m²) (Table 5);

- dominance (D), an index representing the percentage of participation of each species in the catch, ranged between 0.1% (*Anoxia villosa* Fabricius) and 28.2% (*Ostrinia nubilalis* Hbn.), while constancy (C) had values between 11.8% and 94.1.% (Table 5);

- based on the values of the ecological significance index (W), which ranged between 0.01% (*Anoxia villosa* F.) and 26.5% (*Ostrinia nubilalis* Hbn.).

Table 5

Ecological parameters of the entomofauna collected in corn crops, Secuieni-Neamț (2021 - 2024)

No.	Specia	A	D	C	W
1.	*Agriotes* sp.	59	1,6	70,6	1,1
2.	*Anoxia villosa* Fabricius	3	0,1	11,8	0,0
3.	*Melolontha melolontha* L.	12	0,3	29,4	0,1
4.	*Harpalus distinguendus* Duft.	136	3,6	70,6	2,5
5.	*Harpalus rufipes* Degeer	187	5,0	58,8	2,9
6.	*Opatrum sabulosum* L.	23	0,6	35,3	0,2
7.	*Tanymecus dilaticollis* Gyll	57	1,5	35,3	0,5
8.	*Gonocephalum pusillum* L.	16	0,4	35,3	0,1
9.	*Psalidium maxilosum* Fabricius	6	0,2	29,4	0,0
10.	*Lethrus apterus* Laxman	4	0,1	23,5	0,0
11.	*Diabrotica virgifera virgifera* Le Conte	1002	26,6	52,9	14,1
12.	*Ostrinia nubilalis* Hbn.	1064	28,2	94,1	26,5
13.	*Amathes c-nigrum* L.	195	5,2	70,6	3,6
14.	*Helicoverpa armigera* Hbn.	993	26,3	76,5	20,1
15.	*Agrotis segetum* Dennis &Schiff	10	0,3	23,5	0,1
16.	*Schizaphis graminearum* Ron.	6	0.2	17.6	0.0
Total	**16 species**	**3773**	**x**	**x**	**x**

The inventoried species were classified into three classes as follows:

- nine species were classified in class W1, which includes accidental species with an ecological significance index less than 1.0%;

- four species were classified in class W2, which includes accessory species with an ecological significance index between 1.1% and 5.0%, as defined by the class;
- three species, with an ecological significance index above 5.1%, were classified in class W3, which includes characteristic species (Table 6).

Table 6

Classification of pest species by ecological significance index, Secuieni – Neamț (2021 - 2024)

No.	W1	W2	W3
	Sp. Accidental W < 1.0 %	**Sp. Accessories W = 1.1 – 5.0 %**	**Sp. Characteristics W > 5.1 %**
1.	*Tanymecus dilaticollis Gyll*	*Agriotes spp..* *Harpalus distinguendus* Duft. *Harpalus rufipes* Degeer *Amathes c-nigrum* L.	*Ostrinia nubilalis* Hbn. *Diabrotica virgifera virgifera* Le Conte. *Helicoverpa armigera* Hbn.
2.	*Gonocephalum pusillum F.*		
3.	*Opatrum sabulosum L.*		
4.	*Melolontha melolontha L.*		
5.	*Agrotis segetum Den et Schiff.*		
6.	*Psalidium maxilosum F.*		
7.	*Lethrus apterus L.*		
8.	*Schizaphis graminum Ron.*		
9.	*Anoxia villosa F.*		
TOTAL	**nine species**	**four species**	**three species**

CONCLUSIONS

The average annual number of corn crop pests totalled:

- in the period 2002-2011 - 288.2 specimens/m^2
- in the period 2012-2020 – 1832.2 specimens/m^2
- in the period 2021-2024 - 3773 specimens/m^2

The abundance of harmful species was high during the period 2002-2011, reaching its highest values, 49.3%, during the seed germination, emergence, and 3-5 leaf formation stages.

During the periods 2012-2020 and 2021-2024, the highest values of species abundance were recorded during the panicle and tassel emergence period, representing 79.9% and 58.7% of the total catches, respectively.

In terms of the large number of species, as well as the number of specimens, the order Coleoptera held the maximum share, recording values from 40% to 92%.

The proportion of specimens collected from the Order Lepidoptera has increased significantly, especially in the last period analysed, 2021-2024, when the density of the four identified species increased considerably, representing 60% of the total specimens.

We thus observe that the corn crop faces two periods of vulnerability to attack by soil and plant pests, namely:

- The first is represented by the period between germination-emergence-the formation of the first 3-5 leaves, when young plants can be protected by chemical treatments applied to the vegetation to reduce pest populations below the PED.
- The second period is between the appearance of the tassel and the ear, and the formation of the kernels, when the populations of adult pests and larvae increase significantly, and the cumulative attack compromises the grain harvest both quantitatively and qualitatively.

Based on these studies, it can be estimated that the key pests of corn crops during the growing season in the area of influence of SCDA Secuieni are: *Tanymecus dilaticollis* Gyll., *Opatrum sabulosum* L., *Ostrinia nubilalis* Hbn., *Diabrotica virgifera virgifera* Le Conte, and *Helicoverpa armigera* Hbn.

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SUNFLOWER CROP ENTOMOFAUNA DEVELOPMENT IN CENTRAL MOLDOVA CONDITION (ROMANIA)

EVOLUȚIA ENTOMOFAUNEI DĂUNĂTOARE DIN CULTURILE DE FLOAREA - SOARELUI ÎN CONDIȚIILE DIN CENTRUL MODOVEI

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Keywords: *sunflower, entomofauna, pests, evolution, density*

ABSTRACT

The paper presents the dynamics of harmful entomofauna in sunflower crops in the central zone of Moldova during the period 2010–2024. Due to its high economic value, the increase in cultivated areas with this species has also favoured the development of a diverse pest fauna. The results showed that the harmful entomofauna in sunflower crops totalled, on average, 195 specimens/m^2 during the period 2010-2014, 145 specimens/m^2 during the period 2015-2018, and 506 specimens/m^2 during the period 2019-2024. Observations and determinations made showed that the harmful entomofauna consisted of 17 species of specific and polyphagous insect pests during the period 2010-2014, 12 species were identified between 2015-2018, and 16 species during the period 2019-2024. The insect species inventoried in sunflower crops were classified into four systematic orders: Coleoptera, Lepidoptera, Orthoptera, and Homoptera. Based on the number of species collected, the order Coleoptera accounted for the largest share both in terms of the number of identified species and the number of specimens collected, followed by Lepidoptera, Orthoptera, and Homoptera. Based on these studies, it can be concluded that the key pests of sunflower crops during the vegetation period in the area of influence of ARDS Secuieni are: Chaetocnema aridulla Gyll., Crepidodera ferruginea Scopoli, Tanymecus dilaticollis Gyll., and Opatrum sabulosum L. The data obtained confirm the need for continuous monitoring and implementing integrated protection measures to keep harmful species under control and effectively protect sunflower crops in the Moldova region.

ABSTRACT

Lucrarea prezintă dinamica entomofaunei dăunătoare din culturile de floarea-soarelui în zona centrală a Moldovei, în perioada 2010–2024. Creșterea suprafețelor cultivate cu această specie, datorită valorii economice ridicate, a favorizat și dezvoltarea unei faune dăunătoare diversificate. Rezultatele au evidențiat că entomofauna dăunătoare culturilor de floarea - soarelui a totalizat, în medie, în perioada 2010-2014 - 195 exp./m^2, în perioada 2015-2018 – 145 exp./m^2 și în perioada 2019-2024 - 506 exp./m^2. Observațiile și determinările efectuate au arătat că entomofauna dăunătoare a fost alcătuită din 17 specii de insecte dăunătoare specifice și polifage în perioada 2010-2014, 12 specii s-au identificat în intervalul 2015-2018 respectiv 16 specii in perioada 2019-2024. Speciile de insecte inventariate în culturile de floarea – soarelui s-au încadrat în patru ordine sistematice: Coleoptera, Lepidoptera, Orthoptera și Homoptera. După numărul de specii colectate, ordinul Coleoptera a deținut ponderea maximă atât sub numărul de specii identificate, dar și sub aspectul exemplarelor colectate, urmat de Lepidoptera, Orthoptera și Homoptera. În urma acestor cercetări, se poate aprecia că dăunătorii cheie ai culturii de floarea - soarelui, în perioada de vegetație a culturii pentru zona de influență a SCDA Secuieni sunt: Chaetocnema aridulla Gyll., Crepidodera ferruginea Scopoli, Tanymecus dilaticollis Gyll., Opatrum sabulosum L. Datele obținute confirmă necesitatea monitorizării permanente și a aplicării unor măsuri de protecție integrate, pentru menținerea sub control a speciilor dăunătoare și protejarea eficientă a culturilor de floarea-soarelui din regiunea Moldovei.

INTRODUCTION

The sunflower originated in North America, where it was first cultivated by indigenous tribes over 4,500 years ago.

In Romania, this plant is of particular importance, being considered the "transition plant of agriculture" from 1989 to the present. The area cultivated with sunflowers has almost doubled during this period. If between 480,000 and 520,000 hectares were cultivated before 1989, after 1989 the area increased to 980,000 – 1,020,000 hectares. This expansion was primarily due to the favourable price of seeds on the market, but also to the increased interest in sunflower oil, which is used not only in food but also in the production of biofuel (Trotuș, E., et al., 2022).

Due to the sunflower's multiple uses, along with its ease of cultivation with a relatively short growing season, its adaptability to temperature fluctuations, and its drought resistance, the area under cultivation for this plant has expanded over large areas (Popescu, V., 1996).

The cultivation of this economically important species over extensive areas is also accompanied by attacks from pathogens and pests, which are constantly on the rise (Bărbulescu, AL., 2001; Trotuș, E., et al.,1997; Popov C., et al., 2001;).

Pests affect crops in a variety of ways, but the final effect is a reduction in the quantity and quality of the yield. Up to 35 species of pests can be found in sunflower crops. Due to their negative impact, the breeding process has focused on obtaining high seed-producing hybrids with a high oil content and resistance or tolerance to pest attacks (Trotuș, E., et al., 2015, 2022; Teodor, A., et al, 2019; Oprea B.D., et al, 2022).

Due to the attacks and the high density of soil pests, exceeding the economic threshold of damage (ETD), monitoring the appearance, evolution of species, and attacks, as well as experimenting with prevention and control methods, are imperative for sunflower crops in the Central area of Moldova (Dudoiu, R., et al., 2018; Trotuș, E., et al., 2019; Anton F.G., et al., 2024).

This paper presents the evolution of harmful entomofauna in sunflower crops in the Centre of Moldova from 2010 to the present.

MATERIALS AND METHODS

Research on identifying the harmful entomofauna of agricultural crops in the western part of the Central Moldavian Plateau began in 2010 and has continued uninterrupted to the present day, covering a period of 15 years.

The monitoring of pest appearance and development was carried out using various methods:

- soil surveys with a 25/25 cm metric frame,
- collections using yellow bowl traps, Barber traps,
- yellow traps, installed in the field from crop emergence until plant maturity.

The biological material was collected every 10 days and analysed under a binocular microscope, identified by species, and subjected to mathematical analysis to calculate ecological parameters: abundance (A), dominance (D), constancy (C), and the ecological significance index (W), which highlight the characteristics of the analysed biocenosis.

Abundance (A) represents the total number of individuals of a species captured from a specific location on a specific date. Based on the value of this indicator, the other indicators are calculated.

Dominance (D) shows the percentage of participation of each species in the catch. It expresses the relationship between the population size of a species and the sum of the individuals of the other associated species.

This indicator is calculated using the formula: DA = (NA * 100) / N1 NA = the total number of individuals of species A; N1 = the total number of individuals of all collected species.

Dominance classes include species whose percentage of distribution falls within the following values:

D1 – supercooled species – distribution percentage P<1.1%;
D2 - receding species P = 1.2 - 2.0%;
D3 – subdominant species P = 2.1-5.0%;
D4 – dominant species P=5.1-10.0%;
D5 – eudominant species P>10.1%.

Constancy (C) expresses the continuity of a species' presence in the analysed biotope. This characteristic is a structural indicator because it represents the proportion of a species' participation in the

formation of the biocenosis structure. The higher the indicator value, the better adapted the species is to the conditions offered by the biotope.

Constancy is calculated using the mathematical formula: CA = nPA / Np x 100 CA – constancy of species A; nPA – the number of samples in which species A is found;
NP – total number of samples examined.
Depending on the value of this indicator, species are distributed into the following classes:
C1 – accidental species (1-25%);
C2 – accessory species (25.1-50%);
C3 – constant species (50.1-75%);
C4 – euconstant species (75.1-100%).

The ecological significance index (W) represents the relationship between the structural indicator (C) and the productive indicator (D).

The ecological significance index is calculated using the formula: WA = (CA * DA * 100) / 10000, where WA = the ecological significance index of species A; CA = the constant for species A; DA = dominance of species A;

Based on the values obtained, the species are divided into the following classes:
W1 – values below 1% - accidental species class;
W2 – with values between 1.1-5.0% - the class of accessory species;
W3 – with values ranging from over 5.1-10.0% - the characteristic species class, (Buburuz, 2013)

RESULTS

In sunflower cultivation, the entomofauna collected during the period 2010–2014 consisted of 17 pest insect species, both specific and polyphagous.

The highest proportions were recorded for the species *Crepidodera ferruginea* Scop. (30%), *Chaetocnema aridula* Gyll. (17%), *Opatrum sabulosum* L. (11%), *Tanymecus palliatus* F. (9%), and *Agriotes* spp. (7%), while the lowest values were observed for *Aphis fabae* Scop. (1%), *Pentodon idiota* Herbst (1%), and *Anoxia vilosa* F. (1%) (Figure 1).

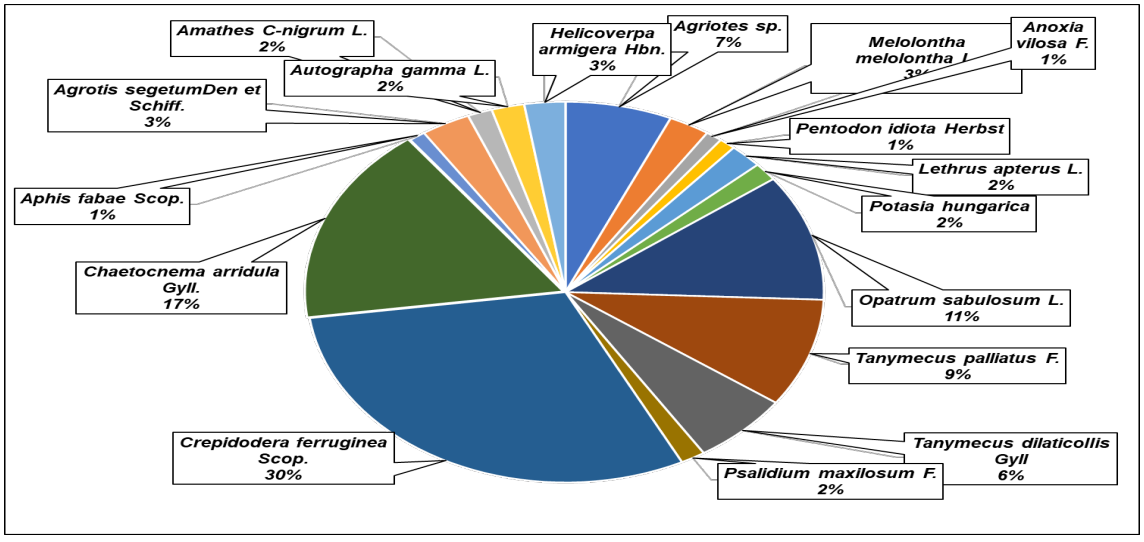


Fig. 1. The share of sunflower crop pests in Secuieni - Neamț, 2010-2014

Between 2015 and 2018, a reduction in the number of identified harmful species was observed, from 17 to 12. The lowest recorded proportion was 1% for the species *Anoxia villosa* F. and *Melolonta melolontha* L., while the highest proportions were obtained for the species *Chaetocnema aridula* Gyll., of 26%, and *Crepidodera ferruginea* Scop., of 43%.

High weights were recorded for the following species: *Crepidodera ferruginea* Scop. (43%), *Chaetocnema aridula* Gyll. (26%), *Opatrum sabulosum* L. (7%), *Agriotes* spp. (6%), *Tanymecus palliatus* F. (4%), and *Tanymecus dilaticollis* Gyll. (3%) (Figure 2).

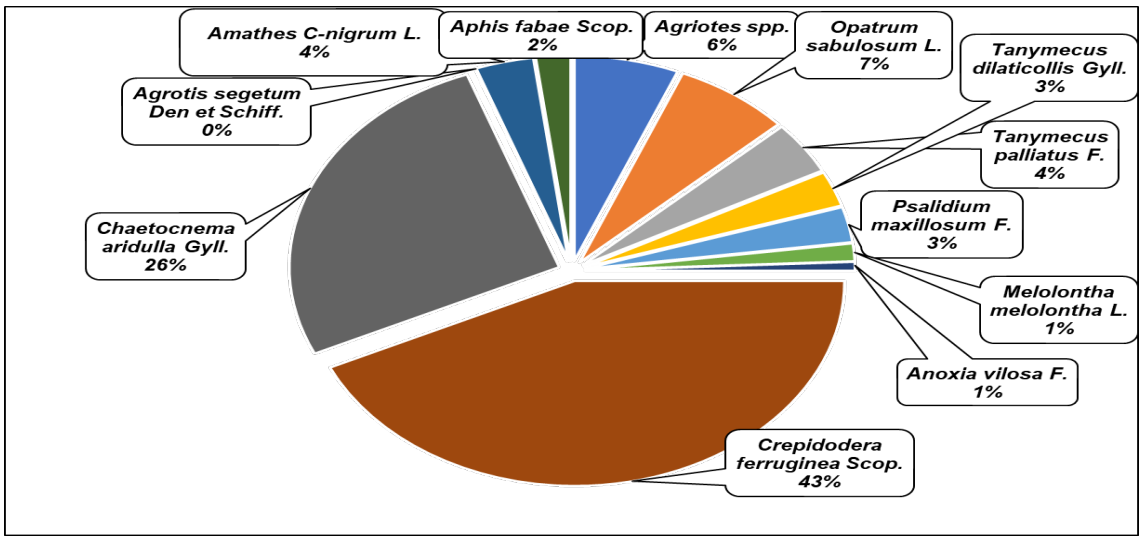


Fig. 2. The share of sunflower crop pests in Secuieni - Neamț, 2015-2018

Between 2019 and 2024, the harmful entomofauna diversified, consisting of 16 species. The highest proportions of identified specimens were recorded for the species *Harpalus* sp., at 36%, *Gryllus campestris* L., at 17%, and *Crepidodera ferruginea* Scop., at 11%, while the lowest proportions of collected specimens were recorded for the species *Melolontha melolontha* L., *Gryllotalpa gryllotalpa* L., *Agrotis segetum* Dennis & Schiff, *Amathes C-nigrum* L., and *Aphis fabae* Scop., at 1% (Figure 3).

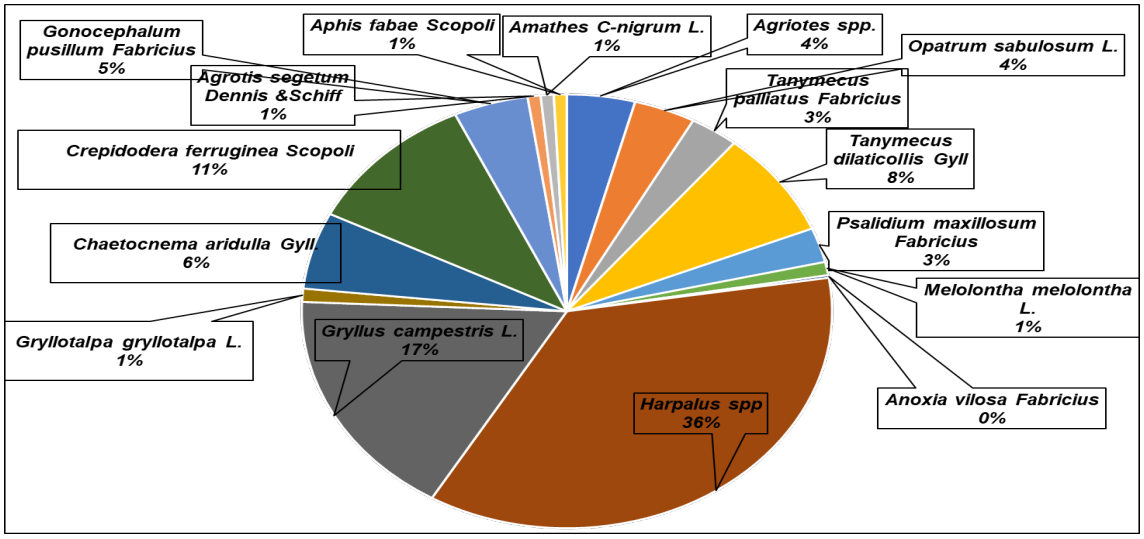


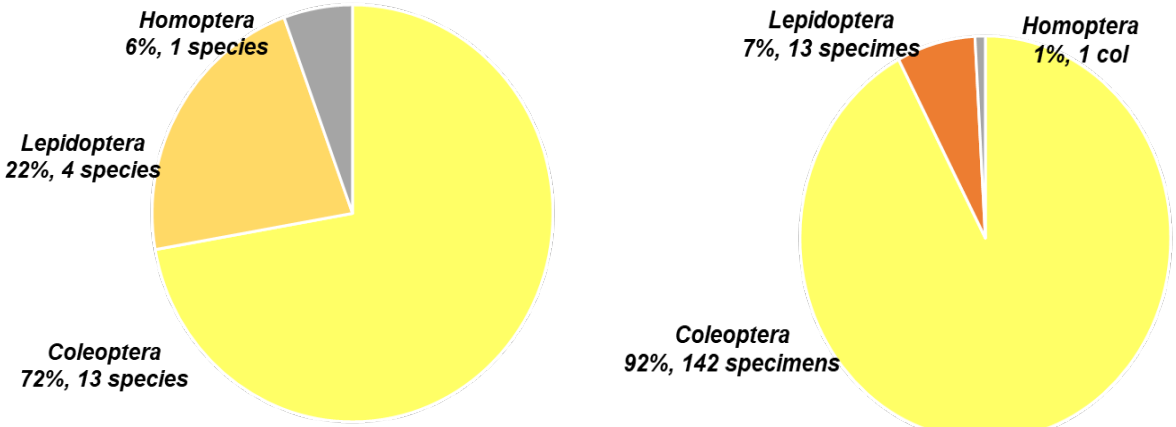
Fig. 3. The share of sunflower crop pests, Secuieni - Neamț, 2019 - 2024

The 17 species inventoried in sunflower crops between 2010 and 2024 belong to the following systematic orders: Coleoptera (13 species), Lepidoptera (four species), and Homoptera (one species). Based on the number of specimens collected, the order Coleoptera accounted for the largest proportion in all monitoring years, at 91% (142 specimens), followed by the orders Lepidoptera, with 8% (13 specimens), and Homoptera, with 1% (1 colony) (Figure 4a).

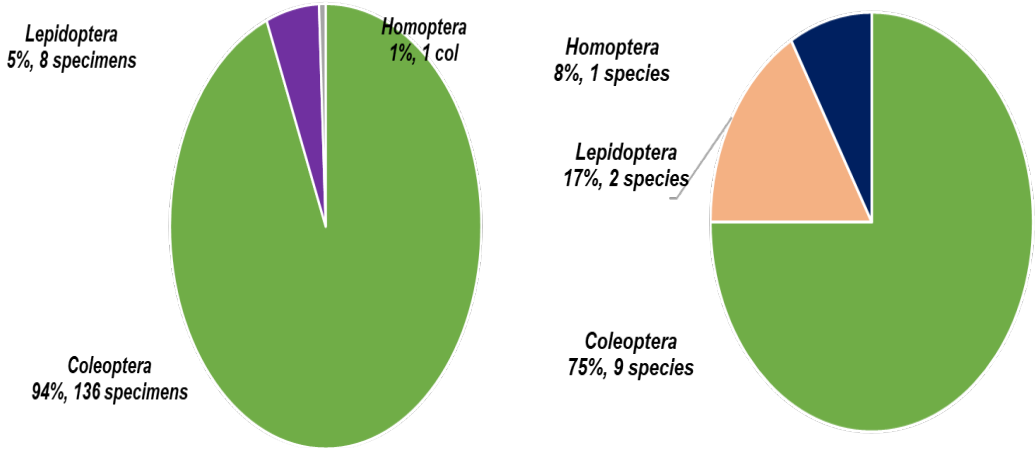
The structure of the systematic orders remained the same between 2015 and 2018, but the number of species decreased to nine species in the order Coleoptera, two species in the order Lepidoptera, and one species in the order Homoptera. Regarding the collected specimens belonging to each order, it is observed that, as in this period, the order Coleoptera recorded the most specimens, representing 94% of the total (136 specimens), followed by the order Lepidoptera with 5% (8 specimens) and Homoptera with 1% (one colony) (Figure 4b).

In the third monitoring period, it is observed that there are changes in the structure of the orders to which the inventoried species in the sunflower crop belong. The proportion of species belonging to the order Coleoptera was 69% (11 species), followed by the orders Lepidoptera and Orthoptera, with 13% (2 species) each, and Homoptera, with 6% (one species). Analysing the number of inventoried specimens from the order

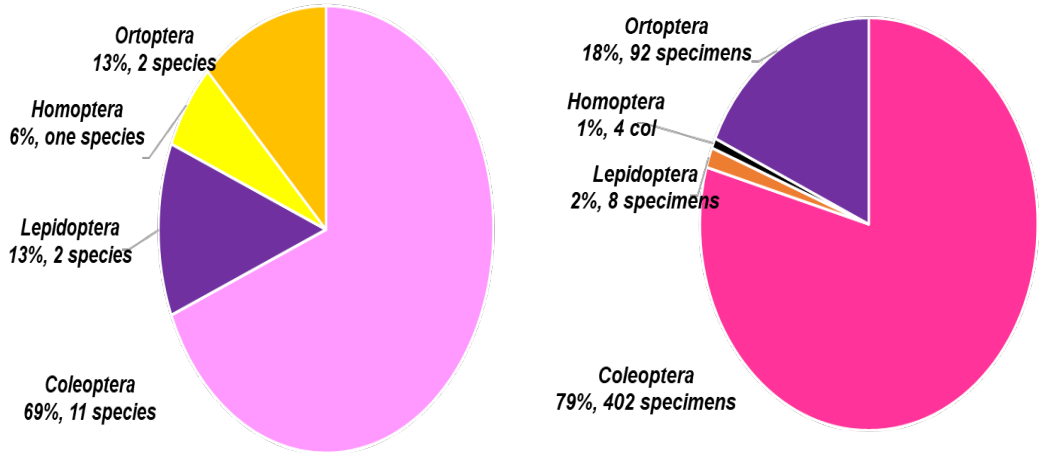
Coleoptera, it is observed that it had the highest proportion, 79%, totalling 402 specimens, followed by the order Orthoptera with 18% (92 specimens), Lepidoptera with 2% (8 specimens), and Homoptera with 1% (4 colonies) (Figure 4c)



a) 2010-2014



b) 2015-2018



c) 2019-2024

Fig. 4: The share of systematic orders based on the number of species and specimens inventoried in sunflower crops, Secuieni - Neamț

Between 2010 and 2014, 17 species of harmful insects were identified in sunflower crops in the Central zone of Moldova, with significant variations in abundance, dominance, constancy, and ecological value. Throughout the entire growing season, their average annual density was 195 specimens (Table 1).

The highest abundances were recorded for the species *Crepidodera ferruginea* Scop. (59 individuals/m²), *Chaetocnema aridula* Gyll. (33 specimens/m²), *Opatrum sabulosum* L. (21 specimens/m²), *Tanymecus paliatus* F. (18 specimens/m²), and *Agriotes* spp. (13 specimens/m²), while the lowest values were observed for *Aphis fabae* Scop. (2 colonies/m²) (Table 1).

The most abundant and ecologically significant species was *Crepidodera feruginea* Scop., with high dominance (30.3%), constant occurrence frequency (33%), and a high ecological value (W3 – 10.1%), followed by *Chaetocnema arridula* Gyll., which also showed high values for all indicators (D5, C2, W2) (Table 1).

The species *Opatrum sabulosum* L. and *Tanymecus palliatus* F. were significantly present, recording high levels of constancy and dominance. In contrast, most other species (including *Anoxia villosa* F., *Pentodon idiota* and *Aphis fabae* Scop.) showed low densities and ecological importance (W1), suggesting a limited impact on the crop during the analysed period (Table 1).

Table 1

Ecological parameters of the entomofauna collected in sunflower crops, Secuieni-Neamț (2010 - 2014)

Nr. Crt.	Species	A	D	C	W
1	*Agriotes sp.*	13	6.7 (D4)	22 (C1)	1,5 (W2)
2	*Melolontha melolontha* L.	5	2.6 (D3)	22 (C1)	0,6 (W1)
3	*Anoxia vilosa* Fabricius	2	1.0 (D2)	11 (C1)	0,1 (W1)
4	*Pentodon idiota* Herbest	2	1.0 (D2)	11 (C1)	0,1 (W1)
5	*Lethrus apterus* Laxmann	4	2.1 (D3)	17 (C1)	0,3 (W1)
6	*Potasia hungarica*	3	1.5 (D2)	17 (C1)	0,3 (W1)
7	*Opatrum sabulosum* L.	21	10.8 (D5)	28 (C2)	3,0 (W2)
8	*Tanymecus palliatus* Fabricius	18	9.2 (D4)	22 (C1)	2,1 (W2)
9	*Tanymecus dilaticollis* Gyll.	12	6.2 (D4)	17 (C1)	1,0 (W1)
10	*Psalidium maxilosum* Fabricius	3	1.5 (D2)	17 (C1)	0,3 (W1)
11	*Crepidodera feruginea* Scopoli	59	30.3 (D5)	33 (C2)	10,1 (W3)
12	*Chaetochnema arridula* Gyll.	33	16.9 (D5)	33 (C2)	5,6 (W2)
13	*Aphis fabae* Scopoli	2	1.0 (D2)	11 (C1)	0,1 (W1)
14	*Agrotis segetum* Dennis &Schiff	6	3.1 (D3)	22 (C1)	0,7 (W1)
15	*Amathes C-nigrum* L.	3	1.5 (D3)	17 (C1)	0,3 (W1)
16	*Autographa gamma* L.	4	2.1 (D3)	17 (C1)	0,3 (W1)
17	*Helicoverpa armigera* Hbn.	5	2.6 (D3)	17 (C1)	0,4 (W1)
Total = 17 species		**195**	**x**	**x**	**x**

The entomofauna collected between 2015 and 2018 recorded abundance values ranging from 1 ispecimens/m² (*Anoxia vilosa* F., *Aphis fabae* Scop.) to 62 specimens/m² (*Crepidodera ferruginea* Scop.). Analysing the classification of species into dominance classes, it is observed that two species belong to class D5 (the class of eudominant species - *Crepidodera ferruginea* Scop. and *Chaetocnema aridulla* Gyll.), two species belong to class D4 (the class of dominant species - *Agriotes* spp. and *Opatrum sabulosum* L.), five species belong to the class of eudominant species – D3 (*Tanymecus palliatus* F., *Tanymecus dilaticollis* Gyll., *Psalidium maxillosum* F., *Agrotis segetum* Dennis & Schiff, *Amathes C-nigrum* L.), one species belongs to class D2 – the class of receding species (*Melolontha melolontha* L.), and two belong to class D1 and are subreceding species (*Anoxia vilosa* F. and *Aphis fabae* Scop.) (Table 2).

Table 2

Ecological parameters of the entomofauna collected in sunflower crops, Secuieni-Neamț (2015 - 2018)

Nr. Crt.	Species	A	D
1	*Agriotes spp.*	9	6.2 (D4)
2	*Opatrum sabulosum* L.	10	6.9 (D4)
3	*Tanymecus palliatus* Fabricius	6	4.1 (D3)
4	*Tanymecus dilaticollis* Gyll.	4	2.8 (D3)
5	*Psalidium maxillosum* Fabricius	4	2.8 (D3)
6	*Melolontha melolontha* L.	2	1.4 (D2)
7	*Anoxia vilosa* Fabricius	1	0.7 (D1)
8	*Crepidodera ferruginea* Scopoli	62	42.8 (D5)
9	*Chaetocnema aridulla* Gyll.	38	26.2 (D5)
10	*Agrotis segetum* Dennis &Schiff	5	3.4 (D3)
11	*Amathes C-nigrum* L.	3	2.1 (D3)
12	*Aphis fabae* Scopoli	1	0.7 (D1)
Total = 12 species		**145**	**x**

Between 2019 and 2024, 16 species of harmful insects were identified in sunflower crops in the Central zone of Moldova, and they were analysed in terms of abundance, dominance, constancy, and ecological value. The most abundant and ecologically significant species was *Harpalus* spp., with high dominance (36%), constant occurrence frequency (61.5%), and a high ecological value (W3 – 22.1), followed by *Gryllus campestris* L. and *Crepidodera ferruginea* Gyll., which also showed high values for all indicators (D4, C2, W2) (Table 2).

The species *Tanymecus dilaticollis* Gyll. and *Chaetocnema aridula* Gyll. were significantly present, recording high levels of constancy and dominance, followed by the species *Agriotes* spp and *Gonocephalum pusillum* Fabricius. The remaining species (*Anoxia villosa* F., *Agrotis segetum* Dennis & Schiff, *Amathes C-nigrum* L., *Aphis fabae* Scop.) recorded low densities and a low ecological importance (W1), indicating a limited impact on the crop during the analysed period (Table 3).

Table 3

Ecological parameters of the entomofauna collected in sunflower crops, Secuieni-Neamț (2019 - 2024)

Nr. Crt.	Species	A	D	C	W
1	*Agriotes spp.*	21	4.2 (D3)	30.8 (C2)	1.3 (W2)
2	*Opatrum sabulosum* L.	19	3.8(D3)	23.1 (C1)	0.9 (W1)
3	*Tanymecus palliatus* Fabricius	15	3.0 (D3)	23.1 (C1)	0.7 (W1)
4	*Tanymecus dilaticollis* Gyll	40	7.9 (D4)	38.5 (C2)	3.0 (W2)
5	*Psalidium maxillosum* Fabricius	13	2.6 (D3)	23.1 (C1)	0.6 (W1)
6	*Melolontha melolontha* L.	5	1.0 (D1)	23.1 (C1)	0.2 (W1)
7	*Anoxia vilosa* Fabricius	1	0.2 (D1)	7.7 (C1)	0.0 (W1)
8	*Harpalus spp*	182	36.0 (D5)	61.5 (C3)	22.1 (W3)
9	*Gryllus campestris* L.	87	17.2 (D4)	46.2 (C2)	7.9 (W2)
10	*Gryllotalpa gryllotalpa* L.	5	1.0 (D1)	15.4 (C1)	0.2 (W1)
11	*Chaetocnema aridulla* Gyll.	29	5.7 (D4)	23.1 (C1)	1.3 (W2)
12	*Crepidodera ferruginea* Scopoli	54	10.7 (D4)	30.8 (C2)	3.3 (W2)
13	*Gonocephalum pusillum* Fabricius	23	4.5 (D3)	30.8 (C2)	1.4 (W2)
14	*Agrotis segetum* Dennis &Schiff	4	0.8 (D1)	15.4 (C1)	0.1 (W1)
15	*Amathes C-nigrum* L.	4	0.8 (D1)	23.1 (C1)	0.2 (W1)
16	*Aphis fabae* Scopoli	4	0.8 (D1)	23.1 (C1)	0.2 (W1)
Total= 16 species		**506**	**x**	**x**	**x**

CONCLUSIONS

1. Pests are a significant limiting factor in the development of sunflower plants under the conditions in the Central Zone of Moldova.

2. The harmful entomofauna in corn crops totalled, on average, 195 specimens during the period 2010-2014, 145 specimens during the period 2015-2018, and 506 specimens during the period 2019-2024.

3. Observations and identifications revealed that the harmful entomofauna consisted of 17 specific and polyphagous insect species during the period 2010-2014, 12 species were identified during the period 2015-2018, and 16 species were identified during the period 2019-2024.

3. The insect species inventoried in sunflower crops were classified into four systematic orders: Coleoptera, Lepidoptera, Orthoptera, and Homoptera.

4. Based on the number of species collected, the order Coleoptera held the largest share both in terms of the number of identified species and the number of specimens collected, followed by Lepidoptera, Orthoptera, and Homoptera.

5. Based on these studies, it can be concluded that the key pests of sunflower crops during the growing season in the area of influence of ARDS Secuieni are: *Chaetocnema aridulla* Gyll., *Crepidodera ferruginea* Scopoli, *Tanymecus dilaticollis* Gyll., and *Opatrum sabulosum* L.

6. For the prevention and control of pests, integrated pest management is recommended, utilising all methods (agrotechnical, chemical, and biological).

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INTELLIGENT MONITORING SYSTEM FOR APPLE ORCHARD PESTS BASED ON PHEROMONE TRAP, ADHESIVE PLATE, AND AI-BASED AUTOMATIC RECOGNITION CORRELATED WITH WEATHER PARAMETERS

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SISTEM INTELIGENT DE MONITORIZARE A DĂUNĂTORILOR ÎN LIVEZILE DE MĂR BAZAT PE CAPCANĂ CU FEROMONI, PLACĂ ADEZIVĂ ȘI RECUNOAȘTERE AUTOMATĂ CU INTELIGENȚĂ ARTIFICIALĂ CORELATĂ CU PARAMETRI METEO

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Keywords: *Smart pheromone trap, AI-based pest detection, Automatic image recognition, Weather-correlated monitoring*

ABSTRACT

This paper presents an intelligent monitoring system for apple orchard pests, integrating a pheromone trap, adhesive plate, and a digital camera with AI-based automatic insect recognition. The system includes a complete weather station, enabling correlation between climatic conditions and pest activity. Solar power ensures autonomous operation, while wireless communication allows real-time data transfer to a digital platform. Results show accurate, continuous monitoring, supporting decision-making in integrated pest management and improving early detection and intervention efficiency.

REZUMAT

Lucrarea prezintă un sistem inteligent pentru monitorizarea dăunătorilor din livezile de măr, bazat pe integrarea unei capcane cu feromoni, a unei plăci adezive și a unei camere digitale cu analiză automată prin inteligență artificială. Sistemul include o stație meteo completă, permițând corelarea parametrilor climatici cu dinamica dăunătorilor. Alimentarea solară asigură funcționare autonomă, iar transmiterea datelor se realizează wireless către o platformă digitală. Rezultatele indică o monitorizare precisă și continuă, cu potențial de utilizare în managementul integrat al dăunătorilor.

INTRODUCTION

Apple orchards represent a strategic sector of fruit production, yet yield and fruit quality are strongly affected by pest attacks, especially those of the codling moth (Cydia pomonella) and other Lepidoptera specific to orchard ecosystems. Phenological modelling studies of the codling moth show that this species is one of the most damaging apple pests worldwide, and the correct timing of treatments depends on understanding its development in relation to temperature and microclimate [6, 10].

The population dynamics of orchard pests are strongly influenced by weather parameters such as temperature, humidity, and precipitation, which highlights the need to integrate climatic information into warning and decision-support systems [15]. Recent research indicates that climate change advances phenophases and increases the number of C. pomonella generations in apple orchards, requiring adapted protection strategies and more refined pest-risk management [9]. Traditional monitoring methods rely on pheromone traps inspected manually, correlated with agrometeorological models (degree-day models) to determine biofix and forecast flight activity [10, 7]. Although effective, these methods are time-consuming, prone to operator errors, and the low observation frequency (typically weekly) limits the temporal resolution of collected data [6].

At the same time, the digital transformation of agriculture and the development of precision farming have led to the emergence of intelligent systems based on the Internet of Things (IoT), capable of collecting real-time field data and supporting automated decisions in crop protection. A relevant example is an IoT system developed for apple orchards that integrates weather and soil sensors for pest and disease forecasting (including C. pomonella), as well as irrigation and fertilization management, significantly reducing the number of phytosanitary treatments [5].

Over the past decade, artificial intelligence (AI) and, particularly, deep learning have become key tools for automatic insect identification from images. Recent reviews highlight the role of convolutional neural networks (CNNs) in pest classification and the support these technologies provide to plant protection decisions [1, 14]. YOLO-based models and other optimized architectures have demonstrated high performance in detecting small-sized pests on sticky plates or colored traps [11, 8]. The practical application of these algorithms in smart traps has led to systems capable of capturing images in real time, detecting and counting insects automatically, and transmitting results to analytical platforms. Embedding deep learning into traps for fruit pests has shown that automated recognition can achieve accuracies comparable to, or even exceeding, human visual inspection [2, 11]. Recent developments, such as the YOLO-pest model integrated into an IoT smart trap, demonstrate that autonomous real-time monitoring can be extended across various crops and climatic contexts [3, 11].

At orchard level, using pheromone traps equipped with cameras and AI algorithms enables continuous pest monitoring, reduces field visits, and improves understanding of spatial and temporal fluctuations in insect populations. Studies conducted in stone fruit and citrus orchards have confirmed the efficiency of camera-based and AI-enhanced traps under diverse climatic and topographic conditions, demonstrating their potential for intensive and sustainable monitoring [4, 2]. Simultaneously, existing commercial digital monitoring solutions combining automatic traps, AI algorithms, and forecasting modules are already used in orchards and other crops to provide real-time warnings and optimize treatment timing [12, 13, 16]. However, many of these systems do not integrate, within a single unit, both automated pest monitoring on adhesive plates and direct measurement of local meteorological parameters at the same observation point.

In this context, developing an intelligent monitoring system for apple orchards—based on a pheromone trap with adhesive plate, equipped with a camera and AI-based automated insect recognition, combined with a local weather station and autonomous data transmission—addresses the need to integrate biotic and abiotic factors into a single platform. Such a system has the potential to provide high-resolution spatio-temporal data essential for integrated pest management, reducing pesticide use and increasing sustainability in modern orchard production [5, 4, 11].

MATERIALS AND METHODS

The intelligent monitoring system was designed as an integrated platform for the automated surveillance of insect pests in apple orchards, combining environmental sensing, optical acquisition, wireless data transmission, low-power embedded control and autonomous energy supply. To ensure that the system performs adequately in real orchard conditions, all components were first evaluated in a controlled laboratory environment, where operating parameters, mechanical stability, optical consistency, communication reliability and energy consumption could be systematically tested. The general architecture adopted for the prototype follows the conceptual digital monitoring scheme illustrated in Figure 1, which outlines the interconnection between the weather station, the smart pheromone trap, the ESP32 acquisition module and the remote server infrastructure.

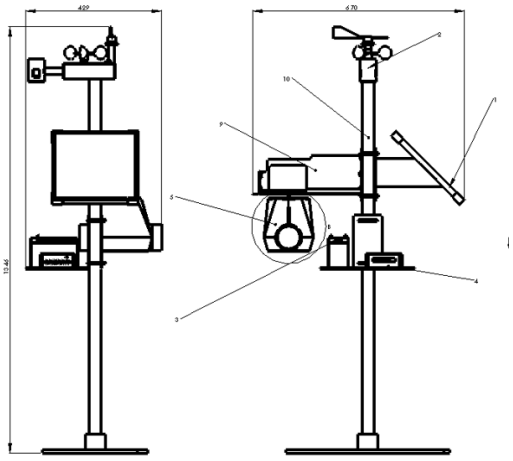

Fig. 1. General schematic of the digital system intended for orchard crop monitoring

The system is structured into three functional subsystems:
(1) an environmental monitoring unit,
(2) an optical capture subsystem integrated into a pheromone trap, and
(3) an ESP32-based acquisition and communication module, powered by a solar-rechargeable energy pack. Each subsystem was independently assembled, verified and subsequently integrated into the complete experimental configuration. The mechanical arrangement was developed to ensure robust support for long-term outdoor operation. The assembly platform consists of a metallic structure designed to host the weather station, sensors and trap, similar to the support shown in Figure 2

Fig. 2. Fixation mechanism of the monitoring unit on the support structure

Control electronics, including the ESP32 main controller, battery, charge controller and wiring, were enclosed in a dedicated housing.

To standardize the interaction between subsystems, a modular wiring methodology was adopted. The rationale behind this modularity is twofold: first, to facilitate rapid replacement or upgrading of sensors and, second, to allow independent testing of individual modules during development. The conceptual interconnection diagram can be represented schematically as follows:

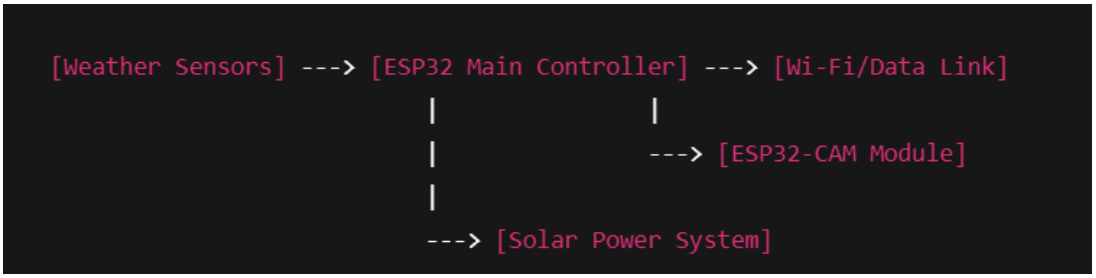

Fig.3. System-level interconnection overview

The environmental monitoring block integrates sensors designed to capture orchard-relevant parameters such as air temperature, relative humidity, wind speed, wind direction, rainfall intensity and solar radiation. Selection criteria included accuracy, low power consumption, Arduino/ESP32 compatibility, robust housings and ease of calibration.

Two redundant temperature and humidity technologies were included:

- SHT31 (I^2C digital sensor), providing high accuracy and low drift
- DS18B20 (OneWire digital sensor), offering robust performance in outdoor conditions

Wind speed and rainfall were represented in laboratory tests through mechanical pulse generators, while solar radiation simulation was achieved using calibrated LED arrays with adjustable luminous flux. These controlled inputs allowed testing of sensor responsiveness without external environmental variability.

Sensor signals were routed into the ESP32 controller through standardized electrical interfaces. A simplified model of the input structure is shown below:

```
Temperature (SHT31)  --> I²C bus
Humidity (SHT31)     --> I²C bus
Temperature (DS18B20) --> OneWire bus
Wind Speed           --> Digital interrupt
Rainfall             --> Digital interrupt
Solar Radiation      --> ADC analog input

All → ESP32 MCU → Data packet → Transmission
```

Fig.4. Sensor interface structure

The ESP32 performed time-aligned sampling using its internal real-time clock. Sensor values were recorded at intervals appropriate for orchard monitoring applications (e.g., every 10–30 minutes).

Smart Pheromone Trap and Optical Capture System

The smart pheromone trap integrates structural features optimized for the attraction and immobilization of targeted pest species. The external geometric model used for fabrication, together with the positioning of internal components, was based on the digital design shown in Figure5

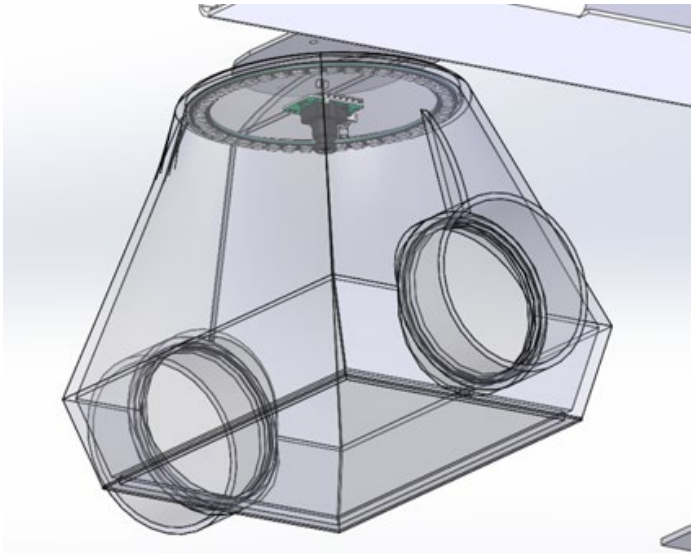

Fig. 5. Smart pheromone trap

Internally, the trap incorporates an ESP32-CAM module equipped with an OV2640 sensor and a ring-shaped LED illumination system. The LED system was selected to minimize shadows and ensure uniform lighting across the adhesive plate. During laboratory tests, printed markers of known size (1–5 mm) were applied to simulate the physical characteristics of insects. These markers were used to evaluate image clarity, contrast and segmentation feasibility.

The mechanical integration process involved assembling all subsystems into a single unit capable of withstanding vibration, humidity and handling. The resulting configuration matches the integrated experimental model illustrated in Figure 6

Fig.6. Full mechanical integration of all monitoring subsystems on the field support pole

Mechanical tests included:

- Vibration exposure, simulating wind-induced oscillations
- High-humidity exposure, assessing condensation resistance
- Repeated manual handling, simulating maintenance operations
- lignment inspection, verifying camera stability

No significant displacement, cable detachment or optical misalignment occurred during testing. This confirmed that the structural design choices documented in the figures from your source document create a stable platform for field deployment.

RESULTS

The intelligent monitoring system developed on an Arduino/ESP32 platform—comprising the weather station, the smart pheromone trap, the ESP32-CAM optical module, and the autonomous energy system—was assembled. All components were evaluated under controlled laboratory conditions to assess their functional stability prior to field deployment. Weather station performance in controlled conditions Although designed for outdoor use, the weather station was tested indoors using an environmental chamber and simulated stimuli. Temperature and humidity sensors (SHT31, DS18B20) responded consistently to controlled variations, remaining within narrow tolerances.or AI-assisted monitoring approaches.

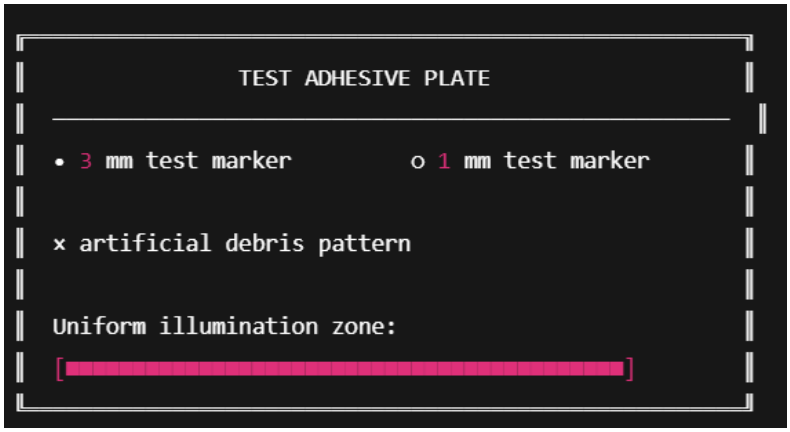

Fig.7. Conceptual representation of laboratory-captured frame

The ESP32 controller correctly recorded and timestamped all measurements, demonstrating stable sensor–microcontroller communication. This behaviour is essential for correlating environmental conditions with pest emergence in later field tests. Optical performance of ESP32-CAM inside the trap The ESP32-CAM

module, mounted inside the trap, ensured constant image quality under controlled LED illumination. Tests used printed markers of 1–5 mm to simulate insects.

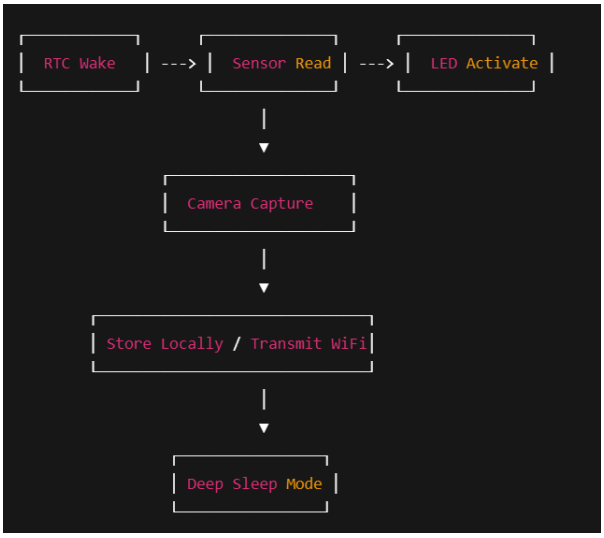

Fig.8. Image acquisition workflow

Illumination uniformity deviation remained below 6%, allowing clear image segmentation. Even the smallest markers (1 mm) were consistently visible, indicating that the combination of camera distance and interior geometry is appropriate for automated identification. The image acquisition sequence triggered by the ESP32 performed reliably during all laboratory cycles. Figure R2 – Image acquisition workflow (Unicode diagram) Wake → LED ON → Capture Image → Store/Send → LED OFF → Sleep All scheduled captures succeeded (100%), confirming robust ESP32–ESP32-CAM communication. Wireless transmission reliability Indoor Wi-Fi tests demonstrated perfect transmission success for both environmental packets and images. JPEG transfers (200–350 kB) required 1.2–2.8 seconds, depending on signal strength. This suggests that under field conditions—where signal variability is expected—the controller remains capable of handling intermittent connectivity. Energy consumption and simulated autonomy Energy consumption was measured using a programmable power supply simulating a solar–battery. Deep sleep consumption was extremely low (0.13 mA), while image capture and upload produced short, predictable peaks.

Measurement	Laboratory Setpoint	Deviation
Air Temperature	20–25 °C	±0.3 °C
Relative Humidity	50–70% RH	±2%
Wind (simulated)	Pulse generator	Stable pulses
Rainfall (sim.)	Manual bucket	Stable pulses
Radiation (sim.)	LED calibrated flux	Linear output

Fig.9. Sensor accuracy under laboratory simulation

Simulations estimate 3.5–4.2 days of autonomy without solar input and over 30 days with partial simulated solar gain. These results indicate that the system is energy-efficient and suitable for long-term outdoor operation. Mechanical and structural validation Mechanical structures evaluated for vibration stability, humidity exposure, and repeated handling. No misalignment of the ESP32-CAM or sensor drift was detected. The internal layout of the trap remained stable, and cable routing resisted condensation during high-humidity tests. Integrated interpretation Overall, the laboratory results confirm that the system's electronics, optics, and mechanical components function reliably when assembled. While the laboratory environment cannot reproduce the dynamic variability of orchard conditions, it provides a controlled framework demonstrating: precise sensor behaviour

consistent optical acquisition stable data transmission predictable energy consumption robust mechanical integration.

Operational Mode	Current Consumption
Deep-sleep (system idle)	0.13 mA
Sensor sampling cycle	25–35 mA
Wi-Fi handshake + upload	110–160 mA
ESP32-CAM capture cycle	180–220 mA
LED illumination event	+150 mA peak

Fig.10. Energy consumption summary

These results suggest that the Arduino/ESP32 architecture, integrated into the documented physical design, offers a solid platform for future field testing and AI-assisted pest monitoring.

CONCLUSIONS

The laboratory evaluation of the intelligent monitoring system based on an Arduino/ESP32 architecture demonstrated that the integrated platform is functionally stable, energy-efficient, and mechanically robust for future deployment in apple orchards. The sensing unit, including temperature, humidity, wind, rainfall and radiation sensors, operated reliably under controlled conditions, ensuring accurate acquisition of environmental parameters. The ESP32-CAM optical module delivered consistent image quality when capturing test markers on adhesive plates, confirming that the trap geometry and illumination configuration support reliable visual monitoring.

Communication tests revealed stable data transfer and full compatibility between the ESP32 main controller and the camera module, while simulated energy cycles indicated that the solar-battery system can sustain long-term autonomous operation with minimal maintenance. Mechanical assessments further showed that fixture stability, enclosure integrity, and cable routing are adequate for outdoor exposure.

The results indicate that the prototype meets the essential functional requirements for an automated pest monitoring system. Although the present study was conducted exclusively in laboratory conditions, the obtained performance metrics validate the system's readiness for field testing and its potential integration with AI-based identification algorithms to support precision horticulture and decision-support tools in orchard pest management.

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MONITORING THE MIGRATION OF THE DANUBE SHAD (ALOSA IMMACULATA) FROM KM 615 (GÂRCOV) TO KM 863 (IRON GATES II) AND THE INFLUENCE OF HYDROCLIMATIC FACTORS
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INFLUENȚA FACTORILOR HIDROCLIMATICI ASUPRA MIGRAȚIEI SCRUMBIEI DE DUNĂRE (ALOSA IMMACULATA) PENTRU SECTORUL GÂRCOV-PORŢILE DE FIER II

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Keywords: *Danube shad, migration, hydroclimatic factors*.

ABSTRACT

The paper presents the results of research on monitoring the migration of the Danube shad (Alosa immaculata) on the Danube sector between km 615 (Gârcov) and km 863 (Iron Gates II), with an emphasis on the influence of hydroclimatic factors. The Danube shad is an anadromous migratory species of great ecological and economic value that carries out its life cycle between the Black Sea and the river, where it reproduces. Its migration is strongly conditioned by factors such as water temperature, the flow and level of the Danube, turbidity and chemical composition of the water. Physico-chemical and hydrobiological analyses of the water revealed a suitable quality for reproduction. The structure of the phytoplankton and zooplankton indicated a moderate specific diversity, dominated by Bacillariophyta and Rotifera.

The study involved experimental fishing and the collection of 208 specimens, analyzed morphologically, biometrically and according to age and sex. The results showed the predominance of 3 and 4 year old specimens, with gonads in stages IV and IV-V, confirming spawning in portions. Prolificity increased with age and gonad stage.

The conclusions emphasize the need to correlate environmental regulations with exploitation regulations to ensure sustainable management of shad stocks, in the context of pressures generated by the presence of the Iron Gates dam, overfishing and climate change.

REZUMAT

Lucrarea prezintă rezultatele cercetărilor privind monitorizarea migrației scrumbiei de Dunăre (Alosa immaculata) pe sectorul Dunării cuprins între km 615 (Gârcov) și km 863 (Porțile de Fier II), cu accent pe influența factorilor hidroclimatici. Scrumbia de Dunăre este o specie migratoare anadromă de mare valoare ecologică și economică ce își desfășoară ciclul de viață între Marea Neagră și fluviu, unde se reproduce. Migrația sa este puternic condiționată de factori precum temperatura apei, debitul și nivelul Dunării, turbiditatea și compoziția chimică a apei. Analizele fizico-chimice și hidrobiologice ale apei au evidențiat o calitate corespunzătoare pentru reproducere. Structura fitoplanctonului și zooplanctonului a indicat o diversitate specifică moderată, dominată de Bacillariophyta și Rotifera.

Studiul a implicat pescuit experimental și colectarea a 208 exemplare, analizate morfologic, biometric și în funcție de vârstă și sex. Rezultatele au arătat predominanța exemplarelor de 3 și 4 ani, cu gonade aflate în stadiile IV și IV-V, confirmând depunerea icrelor în porții. Prolificitatea a crescut odată cu vârsta și stadiul gonadelor. Concluziile subliniază necesitatea corelării reglementărilor de mediu cu cele de exploatare pentru asigurarea unui management durabil al stocurilor de scrumbie, în contextul presiunilor generate de prezența barajului Porțile de Fier, pescuit excesiv și schimbările climatice.

INTRODUCTION

The Danube shad (*Alosa immaculata*) is an important species in the Danube-Danube Delta-Black Sea ecological system and has a high economic value due to the large quantities caught and the taste qualities appreciated by the population in the lower Danube area *(Năvodaru I., 1997)*. Knowledge of the essential elements regarding the biology and exploitation of the species contributes to providing basic information for the conservation of the species and the management of stocks. The development of the life cycle in two environments (freshwater and marine), located at great distances in different periods of time, requires knowledge and updating of the impact of new environmental conditions on the population *(Năvodaru I. 1996)*. Knowledge of the migration of adults for reproduction and the return of juveniles to the sea under the pressure of environmental factors can be used in the development of stock management tactics. Environmental regulations must be associated with exploitation ones so that the biological and socio-economic objectives of the Danube shad fishery can be achieved harmoniously.

The Danube shad (*Alosa immaculata*), figure no. 1, is a migratory fish species of the Clupeidae family, adapted to both marine and freshwater life. It has great ecological and economic importance, being one of the most valuable migratory fish species in the Danube ecosystem *(Bănărescu P., 1964, www.fishbase.org)*.

Fig. 1. Danube shad (*Alosa immaculata*)

Biology of the Danube shad

a). Morphology and general characteristics

- **Size:** 25 - 40 cm long, can reach up to 50 cm;
- **Weight:** 300 - 600 g, but can exceed 1 kg;
- **Appearance:** Fusiform body, laterally compressed, covered with silvery scales;
- **Head and mouth:** Small head, large mouth, lacking obvious teeth;
- **Coloration:** Blue-green back, silvery abdomen and flanks.

b). Life cycle and reproduction

- **Longevity:** 5 - 6 years;
- **Sexual maturity:** at 2 - 4 years, depending on environmental conditions;
- **Reproduction:**
  - anadromous species – migrates from the Black Sea to the Danube for reproduction;
  - spawns in freshwater, in areas with moderate current and sandy or rocky substrate;
  - fecundity: between 30,000 and 120,000 eggs per female.

After spawning, the adults return to the Black Sea, and the fry remain in the Danube for a period of time before migrating to the sea.

Ecology of the Danube shad

a). Habitat and distribution

- It lives mainly in the Black Sea, in coastal areas and in brackish waters;
- Migrates to the Danube and tributaries for reproduction, ascending to the Iron Gates;
- It prefers clean, well-oxygenated waters, with temperatures between 12 - 18° C during the breeding period.

b). Feeding

- in the sea: planktonic feeding – consumes zooplankton, small crustaceans, fish larvae.
- in freshwater: it feeds less, food consumption is reduced during the breeding season.

c). Ecological role

- contributes to the balance of aquatic ecosystems through its migrations, influencing the food chain.
- can be consumed by ichthyophagous birds and predatory fish species (pike perch, catfish, etc.).
- serves as an indicator of water quality, being sensitive to pollution.

d). Limiting factors of migration and conservation of Danube shad (*Alosa immaculata*)

- The construction of dams, for example, the Iron Gates, has limited the breeding range;
- Overfishing and poaching are putting pressure on fish stocks.
- Pollution and climate change, especially global warming, affect reproductive success.

General data on the migration of Danube shad (*Alosa immaculata*)

Fish migration is an essential phenomenon for the maintenance of aquatic ecosystems and the perpetuation of species. The Danube shad (*Alosa immaculata*) is an anadromous migratory fish, which means that it lives in the sea but migrates to the river to reproduce. Knowledge of adult migration for reproduction and the return of juveniles to the sea under the pressure of environmental factors can be used in the development of stock management tactics (*FAO, 2020; FAO, 2021*).

The migration of Danube shad (*Alosa immaculata*) from the Black Sea to the Danube River for reproduction is influenced by a number of essential hydrological factors. These include *(Năvodaru I., 1998; Niculescu Duvăz M., Nalbant T., 1965; Niculescu Duvăz M., 1959)*:

- water temperature

One of the main triggers for migration is rising water temperatures. The peak of migration usually occurs in the second decade of April and the first decade of May, when water temperatures reach values between 9 and 17° C.

- water level and flow rate

Changes in the level and flow of the Danube influence the accessibility and migration conditions for shad. Rising water levels can facilitate the fish's access to breeding grounds, while sudden fluctuations can represent obstacles to migration.

- water turbidity

The degree of turbidity can affect the migratory behavior of shad. More turbid waters can provide protection against predators, but excessive turbidity can negatively influence the orientation and migratory ability of the fish.

- water chemistry

The chemical composition of the water, including dissolved oxygen concentrations and the presence of pollutants, can influence the health and behavior of shad during migration.

These environmental factors play a crucial role in the development of the Danube shad migration, influencing both the timing of its onset and the efficiency of the reproductive process.

MATERIALS AND METHODS

Research methods

Data collection on Danube shad migration

To collect data on the migration of Danube shad (*Alosa immaculata*) schools in the Danube sector from Km 615 (Gârcov) to Km 863 (Iron Gates II), a multidisciplinary approach was used, combining fauna monitoring techniques, ecological studies and community involvement, by following certain essential steps in this process, namely:

a) Preliminary studies
- Identification of the distribution area of the Danube shad and its preferred habitats.
- Study of the bibliography regarding the migration of the species.

b) Field data collection through:
- Organizing expeditions for direct observation of migration;
- Capturing batches, determining the age and performing biometric measurements of the specimens and establishing the prolificity and maturation stage of the females;

c) Collection of data on hydroclimatic factors in the area of the Danube sector of from Km 615 (Gârcov) to Km 863 (Iron Gates II);

d) Monitoring of the physical and chemical parameters of the Danube water in the area from Km 615 (Gârcov) to Km 863 (Iron Gates II) ;

e) Monitoring of the hydrobiological parameters of the Danube water in the area from Km 615 (Gârcov) to Km 863 (Iron Gates II) ;

f) Presentation and analysis of data on research conducted in 2025 on the migration of Danube shad (*Alosa immacuata*) in the sector Km 615 (Gârcov) to Km 863 (Iron Gates II).

Monitoring techniques used

To achieve the proposed objectives, the ichthyological material was collected in the spring (May 2025) in the sector km 615 (Gârcov) to km 863 (Iron Gates II). The ichthyological samples were taken through experimental fishing using floating nets with mesh sizes from 30 x 30 mm to 40 x 40 mm, the set length being 100 m to 200 m, and the set width being 4 - 6 m. The nets were with and without a gillnet. The fishing technique used is schematically shown in table no. 1.

Table 1

Fishing technique used

No.	Fishing technique	Duration (minutes)
1.	Preparing the tools	10 - 20
2.	Travel to the launch site	10 - 40
3.	Launching tools	10 - 15
4.	The actual floating	30 - 40
5.	Removing tools	15 - 25
6.	Untangling the fish	10 - 15
7.	Returning the boat to the fishing spot	10 - 20
8.	Time of fishing (day/night)	day

In figure no. 2 experimental fishing using nets, and in figure no. 3 the untangling of fish from fishing gear (nets), examples of Danube shad caught during experimental fishing.

Fig. 2. Experimental fishing using nets

Fig. 3. Disengaging fish from fishing gear

To cover the migration of shad in time and space samples were extracted from the commercial catches of fishermen. The age, sex, body mass and morphological parameters of the captured fish specimens (208 specimens) were determined. The collection, fixation, processing and determination of the ichthyological material was carried out in accordance with classical ichthyological methods.

The fish were measured with an ichthyometer with an accuracy of 1 mm (total length = TL) (figure 4), weighed with a scale with an accuracy of 1 g (TW) (figure 5), and to determine the age, 10 - 20 scales were collected from the area between the lateral and dorsal lines.

Age determination was done by reading the annual growth rings on the scales using a binocular microscope.

Fig. 4. Specimens of Danube shad caught in experimental fishing

Fig. 5. Body weight recording of Danube shad

Monitoring of physical, chemical and hydrobiological parameters

Water quality monitoring and management, dissolved oxygen, pH and water temperature were measured at each fish collection point. Dissolved oxygen and temperature were measured using a HACH HQ 40d oximeter; pH was measured with a WTW pH meter (Figure 6).

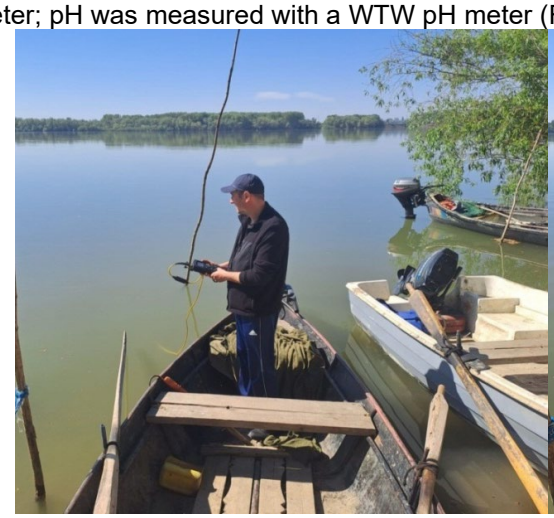

Fig. 6. Recording of water hydrochemical parameters

Fig. 7. Water sample collection for hydrobiology analyses

The environmental conditions were determined by physicochemical and hydrobiological analyses carried out by taking water samples (figure 7) which were subsequently processed in the laboratory. The determination of the main hydrochemical parameters was carried out by known methods. The hydrobiological study involved quantitative and qualitative analysis of plankton (phytoplankton and zooplankton). The values of the quality indicators were analysed and interpreted, according to order no. 161/2006 "Regulations on the classification of surface water quality in order to establish the ecological status of water bodies" approved by the Order of the Minister of Environment and Water Management .

RESULTS

Data on hydroclimatic factors in the area of the Danube sector from Km 615 (Gârcov) to Km 863 (Iron Gates II)

The variability of hydroclimatic factors has a significant impact on the migration of Danube shad in the Danube River. Changes in the hydrological and climatic regime, caused by both natural and human factors, can disrupt the migratory cycle of the species and have negative consequences on the shad population. The implementation of appropriate habitat conservation and management measures, as well as careful monitoring of Danube shad populations, is essential to protect the migration and ensure the ecological stability of the Danube River.

According to the National Institute of Hydrology and Water Management (INHGA), based on medium and long-term statistical elements, the forecast of average and extreme monthly flows on the Danube at the entrance to the country (Baziaş section) was developed for the period February - July 2025, values presented in table no. 2 *(www.hidro.ro).*

Table 2

Average and extreme monthly flows on the Danube at the entrance to the country (February - July 2025)

Flow rates (Q)	February 2025		March 2025		April 2025		May 2025		June 2025		July 2025	
	m.a.		m.a.		m.a.		m.a.		m.a.		m.a.	
Maximum Q (mc/s)		4800		7000		9000		7000		7500		6000
Average Q (mc/s)	5300	3700	6700	5000	7900	7000	7250	5100	6400	6000	5350	4700
Minimum Q (mc/s)		3000		3000		5500		4200		3800		3500

Also, in the table, in the column "m.a." are presented the multiannual average values of the flows corresponding to the months: February, March, April, May, June and July.

According to the National Institute of Hydrology and Water Management (INHGA), the prognostic estimates for the months of February - July 2025 for the studied sector, in the vast majority of cases, the values were within the range of 30 - 80% of the normal monthly values.

Presentation and interpretation of data from the water analysis bulletin at Corabia point

Tables 3 and 4 present the analysis reports of water samples from the Danube in the Corabia area (km 640 and km 648).

Table 3

Analysis bulletin – (water sample, Corabia collection point- km 640 and km 648)

Recorded parameters		*Station 1*	*Station 2*
Dissolved oxygen (mg/l)		8.72	9.04
Saturation (%)		94.3	91.1
Water temperature (°C)	Area (0.5 m)	18.7	18.8
	Depth (3 m)	18.4	18.2

Table 4

Values of water sample analysis report from Corabia collection point compared to values according to MMGA Order 161/2005

FEATURES	M.U.	Sample analyzed 1	Sample analyzed 2	Values according to Ordinance MMGA 161/2006		
				Minimum	Optimum	Maximal
Temperature	°C	18.7	18.8			
pH		7.2	7.2	6.9	7 - 7.8	8 - 8.5

Total hardness		dGH	5.04	5.10	5	12	20
Alkalinity HCl 0.1 N		ml	3.0 + 0	3.12 + 0	0.2	2.0 - 4.0	8
HCO_3^-		mg/l	183.0	190.3	20 -100	200 - 400	600
CO_3^{2-}		mg/l	-	-	-	traces	10.0 - 20.0
Calcium Ca^{2+}		mg/l	23.6	24.4	30	90 -120	160
Magnesium Mg^{2+}		mg/l	7.53	7.29	6	10.0 - 40.0	50.0
$Ca2^+ / Mg2^+$		mg/l	3.13	3.34	2	5	10
Oxidability $KMnO_4$		mg/l	11.36	11.98	5	20	60
O_2-CCO (Mn)		mg/l	2.88	3.03	6	7.0 - 12.0	14.0
P from PO_4^{3+}		mg/l	0.488	0.502	0.005	0.05 - 1.5	3
N from NO_3^-		mg/l	0.324	0.346	1	2.5 - 4	30
N from NO_2^-		mg/l	0.018	0.020	lack	0.03	0.06
Chloride	Cl^-	mg/l	2.12	2.47	6	30	40
	NaCl	mg/l	3.50	4.09	15	20	30
Ammonium NH_4^+		mg/l	0	0	0.05 - 0.5	0.5 - 1	2

Following the hydrochemical analyses of the samples **(Corabia km 640 and Corbia km 648)** , increases/decreases in some parameters that play a role in maintaining the buffering capacity of the water and maintaining a physiological state within the normal range of fish were highlighted.

Monitoring of hydrobiological parameters of Danube water in the area of Corabia km 640 and Corabia km 648

Qualitative and quantitative structure of phytoplankton in the analyzed samples

Following the analysis of water samples from the two areas, a number of 20 species belonging to 3 taxonomic groups were identified, namely: diatoms 13 species, chlorophyceae 5 species and cyanophyceae 3 species. The development of algae in rivers is limited by water currents, most often the appearance of a substantial biomass being attributed to tributaries and sources, such as lakes in their watershed. The numerical density was between 28580 ex/l and 78450 ex/l.

The dominance, in terms of specific diversity, belongs to the *Bacillariophyta* group, representing 54.3% of the total number of identified species, followed by the *Chlorophyceae* group with 23.8% and *Euglenophyceae* with 21.8%.

In the Corabia km 640 area, a number of 19 species belonging to a number of 5 taxonomic groups were highlighted, namely: diatoms 10 species, chlorophyceae 3 species, cyanophyceae 3 species, cryptophyceae 2 species and dinophyceae 1 species. As for the weight, This belongs to the *Bacillariophyta* group with 41.2% of the total species identified, followed by *Chlorophyta* with 26.9%, *Chryptophyta* with 24.4%, *Cyanophyta* 6.4% and *Dinophyta* 1.1% (fig. no. 8). The numerical density was between 68450 ex/l – 78480 ex/l. The phytoplankton biomass was between 18.3 mg/l and 20.9 mg/l.

In the Corabia km 648 area, a number of 14 species belonging to a number of 5 taxonomic groups were identified, namely: diatoms 9 species, chlorophyceae 1 species, cyanophyceae 2 species, cryptophyceae 1 species and dinophyceae 1 species. In terms of weight, this belongs to the *Bacillariophyta* group with 60.4% of the total identified species, followed by *Chlorophyta* with 22.1%, *Chryptophyta* with 10.6%, *Cyanophyta* 6.0% and *Dinophyta* 0.9% (fig. no. 8). The numerical density was between 55380 ex/l – 81350 ex/l. The phytoplankton biomass was between 12.6 mg/l and 18.4 mg/l.

Zooplankton analysis - Research conducted on the qualitative and quantitative composition of zooplankton has highlighted the existence of three systematic groups represented by 17 taxa.

Corabia km 640 zooplankton analysis showed the presence of 18 taxa. The systematic group Rotifera is represented by 12 species, *Copepoda* by 3 species and *Cladocera* by 3 species. The highest share value was obtained by the taxonomic group *Rotifera* (70.5%), followed by the *Copepoda* group (22.3%) and *Cladocera* (7.2%) (fig. no. 9). Regarding the numerical density we can say that: rotifers recorded an average value of 255 ex/l, cladocerans 82 ex/l and copepods 124 ex/l. The total zooplankton biomass recorded for the 3 taxonomic groups was between 1.80 g/m^3 - 2.30 g/m^3.

Corabia km 648 zooplankton analysis showed the presence of 17 taxa. The systematic group Rotifera is represented by 11 species, *Copepoda* by 3 species and *Cladocera* by 3 species. The highest share value was obtained by the taxonomic group *Rotifera* (72.7%), followed by the *Copepoda* group (20.8%) and *Cladocera* (6.5%) (fig. no. 9). Regarding the numerical density we can say that: rotifers

recorded an average value of 232 ex/l, cladocerans 96 ex/l and copepods 135 ex/l. The total zooplankton biomass recorded for the 3 taxonomic groups was between 1.60 g/m^3 - 2.62 g/m^3.

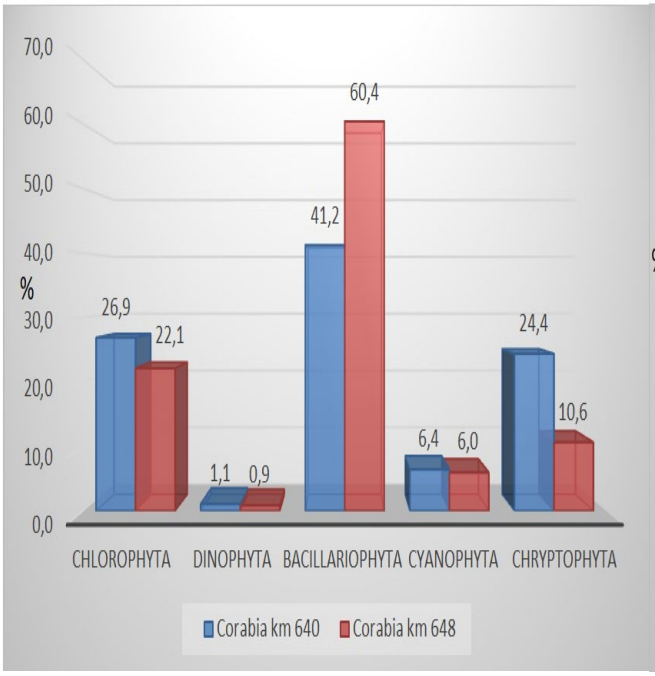

Fig.8. Phytoplankton dynamics in the analyzed areas

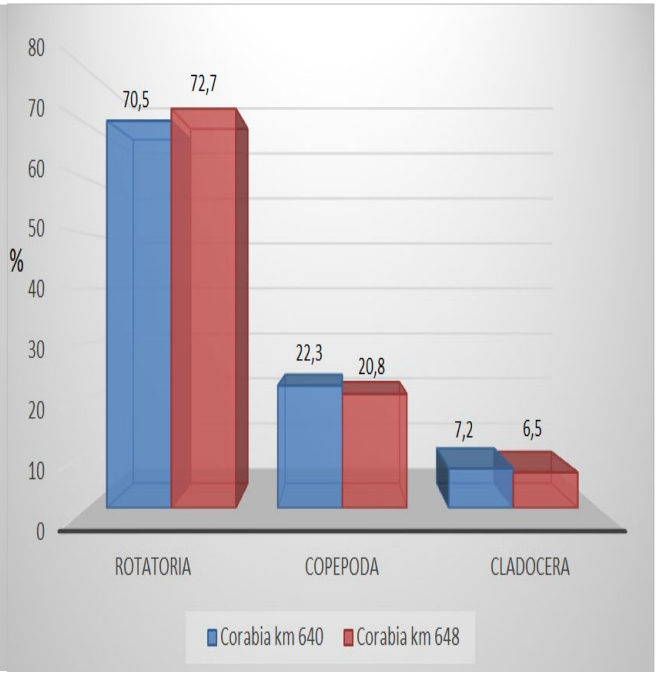

Fig. 9. Zooplankton dynamics in the analyzed areas

Data on research conducted in 2025 on the migration of Danube shad (*Alosa immacuata*) in the sector Km 615 (Gârcov) to Km 863 (Iron Gates II)

The experimental fishing was carried out with nets with and without gillnets and aimed to achieve the following objectives:

- determining the number of fish caught;
- determining the age of fished specimens by reading the annual growth rings on the scales;
- sex determination;
- establishing body mass (g/ex) and body length (Lt.- cm);
- establishing the prolificity and maturation stage of females;

Table 5

Total number of captured specimens and sex ratio of Danube shad

No. crt.	*Capture*	*Ex.*	*%*
1.	Specimens (♂)	106	51.0
2.	Specimens (♀)	102	49.0
3.	**Total**	**208**	**100.0**

Table 6

Data on the number of Danube shad (*Alosa immaculata*) specimens captured and data on age, sex ratio, total length (Lt.- cm), average weight (W- g/ex) determined on the fish material harvested (♂/♀) +(♀)

Specifications	Stock				Total/limits
Age in years	2	3	4	5	
Number of exemplars	14	96	80	18	**208**
Sex ratio (♂ / ♀)	8/6	52/44	37/43	9/9	**106/102**
Total length (Lt.) - cm (♂ + ♀)- average/year	25.0/27.8/ **26.4**	30.0/32.4/ **31.2**	32.5/36.5/ **34.5**	35.0/38.2/ **36.5**	**26.4- 36.5**
Total length (Lt.) - cm (♀) - limits/average	26.1 - 29.5/ **27.8**	30.8 - 34.1/ **32.4**	34.6 - 38.4/ **36.5**	37.2 - 39.0/ **38.1**	**27.8 - 38.1**
Average weight (W.) - g/ex (♂ + ♀)	128/136 **/132**	251/266/ **256**	294/311/ **303**	343/358/ **351**	**132- 351**
Average weight (W.) - g/ex (♀) limits/average	128 - 144/ **136**	258 - 274/ **266**	296 - 326/ **311**	351 – 365/ **358**	**136 - 358**

According to the data presented in tables 5 and 6, the following aspects are highlighted, namely:

- the total number of Danube shad (*Alosa immaculata*) specimens resulting from the experimental fish are 208 specimens, of which 106 specimens are males (♂) and 102 specimens are females (♀);
- by age, total captured specimens, of which males (♂) and females (♀) are:
  - 2 years: 14 individuals, of which 8 males (♂) and 6 females (♀);
  - 3 years: 96 individuals, of which 52 males (♂) and 44 females (♀);
  - 4 years: 80 individuals, of which 37 males (♂) and 43 females (♀);
  - 5 years: 18 individuals, of which 9 males (♂) and 9 females (♀);
- in terms of age, out of the total number of Danube shad (*Aosa immaculata*) specimens captured, the predominant ones are those aged 3 years (96 individuals/52♂+44♀), respectively 4 years (80 individuals/37♂+ 43 ♀).

Following biometric measurements that determined total length (Lt. – cm) and body mass (W - g/ex), the following data were recorded:
- the total length (Lt. – cm) as a general average value measured for all specimens of Danube shad (*Alosa immaculata*), males (106 ♂) and females (102 ♀) at all ages is within the range of 26.4 – 36.5 cm, and the body mass (W- g/ex) within the range of 132 – 351 g/ex;
- both in terms of total length (Lt. – cm) and body mass (W – g/ex), the values of these parameters are lower in males, regardless of age;

In female specimens (♀), the following average values for each age of the two biometric parameters (Lt. – cm and W. – g/ex) were determined and from the data in the table the following values are recorded:
- for all four ages, the total length value (Lt. – cm) is between 27.8 cm (2-year-old female) and 38.1 cm (5-year-old female), the parameter values increase with age.
- for all four ages, the body mass value (W. – g/ex) increases with age and is between 136 g/ex (2-year-old female) and 358 g/ex (5-year-old female).

Data on the degree of maturation and prolificity of Danube shad (*Alosa immaculata*) spawners in the Danube sector km 615 (Gârcov) to km 863 (Iron Gates II)

To determine the stage of gonadal development, a number of 50 females (♀) were studied, only those aged 3 and 4 years, respectively, which were numerically predominant in the shad batches captured, 25 from each age group (25 3-year-old ♀ out of 44 captured and 25 4-year-old ♀ out of 43 captured).

Table 7

Degree of gonadal development in female Danube shad fished in the Danube sector km 615 (Gârcov) to km 863 (Iron Gates II)

Specification	*Stages of gonadal development*					
Number of females ♀*(ex)*	III	III - IV	IV	IV - V	V	Total ♀
Age	3 years					
	-	3	7	11	4	25
Age	4 years					
	-	2	6	14	3	25
Recapitulation						
Age	3 + 4 years					
Total	**-**	**5**	**13**	**25**	**7**	**50**

From the data presented in table no. 7 it results that of the females studied both for the two ages (3 years, 4 years) and for the two ages taken together, the specimens in the IV - V stage of maturation predominate (25 ♀ /11 ex ♀ - 3 years /14 ex ♀ - 4 years) and grade IV (13 ex ♀/7 ex ♀- 3 years - 6 years/16 ex ♀- 4 years). Stage III – IV of gonadal development was identified in a number of 5 ex females, of which 3 ex ♀ aged 3 years and 2 ex ♀ aged 4 years, and grade V in 7 ex ♀ (4 ex ♀ aged 3 years and 3 ex ♀ aged 4 years).

Female Danube shad (*Alosa immaculata*) aged 2 years (6 ex ♀) and 5 years (9 ex ♀) were not studied to determine the degree of gonadal maturation due to the low number of specimens captured.

From the point of view of the degree of gonadal development determined in 3-year-old and 4-year-old specimens, it results that all female Danube shad (*Alosa immaculata*) captured in the Danube sector studied, namely the area between km 615 (Gârcov) and km 863 (Iron Gates II), were ready for reproduction (spawning) according to sexual maturity defined by the degree of gonadal development.

The examination of males regarding reproductive capacity revealed the certainty that approximately 95% of the total specimens examined (10 specimens from the two predominant age groups (3 + 4 years) were ready for reproduction (sperm release), the stage of gonadal development being evaluated at IV and V, respectively.

Data on the gonosomatic ratio in female Danube shad (*Alosa immaculata*) in the Danube sector km 615 (Gârcov) to km 863 (Iron Gates II)

The gonosomatic ratio (maturity index) in Danube shad (*Alosa immaclata*) is directly dependent on the stage of gonadal development (table 8), the highest average value of the gonosomatic ratio is recorded in females, regardless of age, in stage IV (15.84), 10.38 (stage III – IV), 10.30 (stage IV – V) and 9.31 (stage V).

Table 8

Average values and limits of variation of the gonosomatic ratio for the two age groups (3 + 4 years) in female Danube shad (*Alosa immaculata*)

Age (♀)	Stage	No. of exemplars	Gonosomatic ratio (average values)	
			Average	Variation limits
3 + 4 years	III - IV	5	10,38	7,75 - 13,00
	IV	13	15,84	13,55 - 18,13
	IV - V	25	10,30	8,53 - 12,06
	V	7	9,31	8,68 - 9,93
Total/ averages		**50**	**-**	**7,75 - 18,13**

Results obtained regarding the prolificity of Danube shad (*Alosa immaculata*) in the Danube sector km 615 (Gârcov) to km 863 (Iron Gates II)

To determine the prolificity of the Danube shad (*Alosa immaculata*), egg samples were taken from 22 female specimens (♀) aged 3 years , of which 7 ex (♀) with stage IV of gonadal development, 11 ex (♀) with stage IV - V and 4 (♀) with stage V and from 23 ex (♀) 4-year-old females, of which 6 ex (♀) with stage IV of gonadal development, 14 ex (♀) with stage IV - V and 3 ex (♀) with stage V (table 9).

Table 9

Values of the number of eggs/gram determined in female Danube shad (*Alosa immaculata*) depending on age, stage of gonadal development and egg category

Age (years)	Development stage of gonads	No. of exemplars	Number of eggs/gram			
			Category I		Category II	
			Averag	Limts	Average	Limts
3	IV	7	2.120	1.850 - 2.390	2.052	1.354 - 2.750
	IV - V	11	2.574	2.240 - 2.908	1.845	1.020 - 2.670
	V	4	1.120	966 - 1.274	1.032	912 - 1.152
Total/limits	**-**	**22**	-	**966 -2.908**	-	**912 - 2.750**
4	IV	6	2.462	2.021 - 2.903	1.750	1.706 - 1.794
	IV - V	14	2.548	2.248 - 2.848	1.894	1.466 - 2.322
	V	3	1.830	1.686 -1.974	1.550	1.300 -1.800
Total/limits	**-**	**23**	-	**1686 - 2.903**	-	**1.300 - 2.322**

Depending on the stage of development of the gonads and the size category of the eggs (category I and category II), the number of eggs per female (♀) and the number of eggs per 1 g of eggs were determined;

The data regarding the number of eggs/gram show that the highest number was determined in females whose eggs are in the IV - V degree of gonadal development for both 3-year-old and 4-year-old specimens, for both categories of eggs;

- the average values of the number of eggs/g are 2,574 eggs/g for category I eggs and 1,845 eggs/g for category II eggs in 3-year-old females;
- in 4-year-old females, the number of eggs/g data reveals the same aspect, the number of eggs/g is higher in stage IV - V of gonadal development for both categories of eggs (2,548 eggs/g/category I, respectively 1,894 eggs/g/category II);
- as with the number of eggs/female (♀) and the number of eggs/gram, there is an increase in the number of eggs/gram in relation not only to age, but also to the passage of the gonads from stage IV (average 2,361) to stage IV - V (average 2,731), then a decrease in the number of eggs/gram in females with stage V of gonad development (average 1,246);

CONCLUSIONS

As a result of the experimental fishing carried out in the Danube sector km 615 (Gârcov) to km 863 (Iron Gates II) in May, a number of 208 specimens of Danube shad (*Alosa immaculata*) were captured, of which 106 males (♂) and 102 females (♀), grouped into four age categories: 2, 3, 4 and 5 years respectively;

- in terms of age, both females and males were dominated by 3-year-old specimens (96 ex – 52 ex♂ + 44 ex♀), respectively 4-year-old specimens (80 ex – 37 ex♂ + 43 ex♀);
- as a result of biometric measurements that involved determining total length Lt (cm) and average weight W (g/ex), 3 value classes were established for the Lt indicator and four for the W indicator.
- regardless of age, stage or size, eggs of different sizes (categories) were identified in the gonads of Danube shad (*Alosa immaculata*), which certifies that spawning occurs in portions;
- the shad specimens that make up the schools within the studied sector are mostly with gonads in stages IV and IV - V and fewer in stages III - V and V;
- following the data of the prolificity parameters, a gradual increase is observed in both the number of eggs/♀ and the number of eggs/g (average values and variation limits), in relation not only to age, but also to the passage of the gonads from stage IV to stage IV - V of gonad development.

The relatively "stable" situation of natural variation in the size of shad populations can be a trap in the conservation and sustainable exploitation of stocks because some negative environmental and overexploitation effects can manifest themselves many years after the phenomena have occurred.

Currently, there is a need to correlate environmental regulations with exploitation regulations to ensure sustainable management of shad stocks, in the context of pressures generated by the presence of the Iron Gates II dam, overfishing and climate change.

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RESEARCH ON THE FORTIFICATION OF BAKERY PRODUCTS WITH *SPIRULINA* POWDER, INTENDED FOR DIABETICS AND THE OBESE

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CERCETĂRI PRIVIND FORTIFIEREA CU SPIRULINĂ PULBERE, A PRODUSELOR DE PANIFICAȚIE, DESTINATE DIABETICILOR ȘI OBEZILOR

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Keywords: *Spirulina, powder, bakery products, diabetes, obesity*

ABSTRACT

Diabetes mellitus is a chronic disease with an increasing incidence at both national and international levels. In Romania, diabetes mellitus has become one of the most common chronic conditions, with prevalence rates rising from year to year. Currently, 1 in 10 Romanians has diabetes mellitus, and 3 in 10 Romanians have prediabetes, a metabolic condition that can subsequently lead to the development of type 2 diabetes. Under these circumstances, the development of bakery products suitable for diabetic diets is of considerable interest.This paper presents the results of research conducted to develop a low-carbohydrate mini-baguette fortified with Spirulina powder. This product contains 40.00 % total carbohydrates and 30.78 % available carbohydrates and is characterized by a high protein content (14.42%), mineral elements (K = 333.27 mg/100 g; Mg = 102.24 mg/100 g; Ca = 72.18 mg/100 g; Fe = 4.01 mg/100 g; Zn = 2.75 mg/100 g; Cu = 1.10 mg/100 g), bioactive compounds (total polyphenols = 173.25 mg GAE/100 g), and exhibits antioxidant capacity (1.87 mg Trolox equivalents/g). Due to its complex biochemical composition, the low-carbohydrate mini-baguette fortified with Spirulina powder is adapted to the metabolic needs associated with diabetes mellitus and may be successfully incorporated into the diet of individuals with diabetes and obesity.

REZUMAT

Diabetul zaharat este o boală cronică cu incidență crescută atât la nivel național, cât și la nivel internațional. În România, diabetul zaharat a devenit una dintre cele mai frecvente afecțiuni cronice, iar cifrele cresc de la an la an. În prezent, 1 din 10 români are diabet zaharat, iar 3 din 10 români au prediabet, o condiție metabolică ce duce ulterior la instalarea diabetului de tip 2. În aceste condiții, asigurarea unor produse de panificație, adecvate dietei diabetice, este de un real interes. În această lucrare sunt prezentate rezultatele cercetărilor întreprinse pentru realizarea unei minibaghete hipoglucidice, fortifiată cu Spirulină pulbere. Acest produs are un conținut în glucide totale (40,00%), respectiv, glucide disponibile (30,78%) și se remarcă prin conținutul în proterine (14,42%), elemente minerale (K = 333,27 mg/100g; Mg = 102,24 mg/100g; Ca = 72,18 mg/100g; Fe = 4,01 mg/100g; Zn = 2,75 mg/100g; Cu = 1,10 mg/100g), compuși bioactivi (polifenoli totali = 173,25 mg GAE/100g) și prezintă capacitate antioxidantă (1,87 mg Echivalenți Trolox/g). Datorită compoziției biochimice complexe, minibagheta hipoglucidică, fortifiată cu Spirulină pulbere este adaptată nevoilor metabolice din diabetul zaharat și poate fi introdusă în dieta diabeticilor și obezilor.

INTRODUCTION

Type 2 diabetes mellitus (T2DM) is a chronic metabolic disorder characterized by insulin resistance and pancreatic beta-cell dysfunction, leading to elevated blood glucose levels *(Gieroba et al., 2025)*. In 2021, 537 million people worldwide (1 in 10 adults) were living with diabetes, and this number is estimated to reach 783 million by 2045. Type 2 diabetes mellitus is by far the most common form of diabetes, accounting for approximately 90% of cases globally *(Sun et al., 2022)*.

Bread is a staple food in the diet of many population groups at both national and international levels. However, it is also a major source of cereal-derived carbohydrates. A high intake of refined cereals with low dietary fiber content and a high glycemic index is associated with an increased risk of type 2 diabetes mellitus and other chronic diseases. Therefore, improvements in bread composition could have a significant

impact on population health (*Schadow et al., 2023*). A high intake of whole grains is associated with a reduced risk of type 2 diabetes and cardiovascular diseases, while soluble fibers from oats and barley, namely β-glucans, have been shown to reduce blood cholesterol levels and postprandial glycemia (*Hjorth et al., 2025*).

Tătaru et al. (2024) developed a mini-baguette fortified with spirulina (fortification level of 3%). This mini-baguette exhibited superior sensory qualities and was distinguished by its content of proteins (14.60%), lipids (10.02%), total dietary fiber (3.75%), minerals (Fe = 40.75 mg/kg; Zn = 6.06 mg/kg; Mn = 8.37 mg/kg), and total polyphenols (97.22 mg GAE/100 g), as well as by its antioxidant capacity (163 mg Trolox equivalents/100 g).

Catană et al. (2022) developed a mini-baguette fortified with Jerusalem artichoke flour, characterized by a low content of available carbohydrates (43.93–44.37%) and a high content of proteins (11.60–12.15%), minerals (K: 245.17–260.85 mg/100 g; Ca: 136.21–145.21 mg/100 g; Mg: 90.02–98.45 mg/100 g; Fe: 1.88–1.97 mg/100 g; Zn: 1.47–1.56 mg/100 g), total dietary fiber (8.94–9.75 g/100 g), and total polyphenols (115.75–118.98 mg GAE/100 g). This low-carbohydrate mini-baguette also exhibited antioxidant capacity (125.43–128.65 mg Trolox equivalents/100 g) and was intended for individuals with diabetes.

Burnete et al. (2020) developed a bread for diabetics which shows superior sensory quality, high nutritional value and antioxidant potential. It has a low content of available carbohydrates (38.56-39.49%) and is noted for its content in protein (8.85-9.12%), total fiber (3.15-3.70%) and total polyphenols (100.85-115.12 mg GAE/100 g). At the same time, this product has an antioxidant capacity (117.45-125.15 mg TE/100 g).

Spirulina is notable for their protein content (62.49-66.17%), total fiber (5.92-8.86%), total ash (6.22 - 10.47%), vitamins (vitamin C: 55.45-82.73 mg/100 g; vitamin B1: 0.627-1.08 mg/100 g; vitamin B2: 2.12-3.84 mg/100 g; vitamin B3 (Niacin): 8.21- 12.83 mg/100 g; vitamin B5: 2.15-3.05 mg/ 100 g; vitamin B6: 0.653-0.875 mg/100 g; vitamin B9: 0.327-0.588 mg/100 g; vitamin B12: 0.105-0.127 mg/100 g), total polyphenols 154.50 -256.26 mg GAE/100 g), mineral elements (Na:85.77-120.45 mg/100 g; K:1385.37-1678.72 mg/1100 g; Ca: 850-1185.57 mg/100 g; Mg: 205.34-248.93 mg/100 g; Fe: 21.32-46.58 mg/100 g; Zn: 1.23-1.85 mg/100 g). Due to its high antioxidant content, *Spirulina* has antioxidant capacity (5.42-9.12 micromol Trolox/g) (*Catană et al., 2023*).

This paper presents the results of research on the fortification of bakery products (mini-baguettes) with spirulina powder, aimed at individuals with diabetes and obesity.

MATERIALS AND METHODS

The ingredients used and the proposed technological solutions were aimed at reducing the glycemic index on one hand, and increasing antioxidant capacity on the other. The fortification of the bakery product with spirulina (fortification level of 4%) was intended to enhance the nutritional value and antioxidant potential of the mini-baguettes designed for individuals with diabetes and obesity.

Fig. 1- Aspects of the technological process for obtaining the product "Low-carb mini-baguette fortified with *Spirulina*"

For the qualitative characterisation of the product "Low carb mini-baguette fortified with *Spirulina*" were used standardized methods and developed and validated methods in IBA Bucharest. Measurement of the color parameters of samples was performed at room temperature, using a CM-5 colorimeter (Konica Minolta, Japan), equipped with SpectraMagic NX software, to register CIELab parameters (L*, a*, b*). The

moisture content was determined according to the AACC 44-15A method. Protein content was determined by the Kjeldahl method with a conversion factor of nitrogen to protein of 6,25 (AOAC Method 979.09, 2005). Fat content was determined according to AOAC Method 963.15, ash content according to AOAC Method 923.03 (AOAC, 2005) and AOAC 985.29 (total dietary fiber). Total carbohydrate content (%) was estimated by subtracting water, fat, protein and ash content from 100%. The energy value calculation (kcal/100 g and kJ/100 g) was carried out according to the provisions of Commission Regulation no. 1169/2011 (European Commission, 2011).

Determination of iron, copper and zinc was performed by Inductively Coupled Plasma Mass Spectrometry (ICP-MS, model NexION300Q, Perkin Elmer) after dry digestion of the samples. The determination of potassium, calcium and magnesium was carried out by High-Resolution Continuum Source Atomic Absorption Spectrometry (Analytik Jena, model contrAA 700 - High-Resolution Continuum Source Atomic Absorption Spectrometer), flame technique, after dry digestion of the samples.

Total phenolic content was determined by Folin-Ciocalteu procedure, and antioxidant capacity by DPPH method (*Horszwald and Andlauer*, *2011* with some modifications (concerning extraction media, time and mode of extraction, extract volumes of the used sample and reagents, using UV-VIS Jasco V 550 spectrophotometer).

The microbiological analysis was performed using the following methods: SR ISO 21527-1:2009 (Yeasts and molds), SR EN ISO 21528-1:2017 method (*Enterobacteriaceae*), ISO 21807:2004 (Water activity). Water activity was determined using Aquaspector AQS 31 equipment.

RESULTS

Following the sensory analysis of the product "Low-carb mini-baguette fortified with *Spirulina*" it was found that the addition of spirulina powder to its formulation does not affect its taste or aroma. Thus, this bakery product is well-developed, has an elongated shape, a matte surface sprinkled with white sesame seeds, and a uniform brown crust (Fig. 2). Additionally, the mini-baguette has an elastic, dense crumb with uniform pores, characteristic of a well-baked product, with a brown color, free of lumps, and exhibits pleasant taste and aroma.

Fig. 2 - Product "Low carb mini-baguette fortified with *Spirulina*"

The addition of *Spirulina* powder causes a darkening of the low-carb mini-baguette, which is reflected in a low lightness value: L* = 54.21. The color parameter b* (yellow–blue coordinate: -b = blue, +b = yellow) was 13.74, while the color parameter a* (green–red coordinate: -a = green, +a = red) was 3.85.

Physicochemical analysis showed that the product *"*Low-carb mini-baguette fortified with *Spirulina"* has a reduced carbohydrate content (40%), including available carbohydrates (30.78%), and is notable for its protein content (14.42%), ash (2.46%), and total dietary fiber (9.22%) (Table 1). It is worth noting that this fortified mini-baguette, according to the provisions of Regulation (EC) No. 1924/2006 of the European Parliament and of the Council, can be considered a source of protein, as at least 12% of its energy value comes from protein (in this case, 21.36%), and a source of fiber, since its fiber content exceeds 6% (8.90%).

Due to its high fiber content, this mini-baguette has a smaller volume (222 cm³/100 g). The results regarding the volume of the *Spirulina*-fortified mini-baguette are consistent with those reported by *Lopez et al. (2023)*, who noted that the addition of *Spirulina* biomass to bread formulation affects bread weight and volume. Furthermore, the product *"*Low-carb mini-baguette fortified with *Spirulina"* is a source of minerals: K

= 333.27 mg/100 g; Mg = 102.24 mg/100 g; Ca = 72.18 mg/100 g; Fe = 4.01 mg/100 g; Zn = 2.75 mg/100 g; Cu = 1.10 mg/100 g.

Table 1

The physico-chemical indicators of the "Low carb mini-baguette fortified with *Spirulina*"

Physico-chemical indicators	*Haematococcus pluvialis* microalgae
Moisture (%)	35.23±0.63
Volume (cm^3/100 g)	222±1.11
Mass (kg)	0.098±0.002
Acidity (degrees)	3.35±0.02
Ash (%)	2.46±0.04
Protein (%)	14.42±0.23
Fat (%)	7.89±0.10
Carbohydrates (%)	40.00±0.40
Available carbohydrates (%)	30.78±0.26
Total fiber (%)	9.22±0.18
Salt (NaCl) (mg/100g)	0.78±0.004
Energy value (kcal/100g)	270
Energy value (kJ/100g)	1134

The protein content of the product *"*Low-carb mini-baguette fortified with *Spirulina"* is comparable to that reported by *Tătaru* and *Iatco (2024)* for the *"*Mini-baguette fortified with *Spirulina"* (Protein = 14.60%), but higher than that reported by *Catană et al. (2022)* for the *"*Mini-baguette fortified with Jerusalem artichoke flour*"* (Protein = 11.60–12.15%). Additionally, the *"*Low-carb mini-baguette fortified wit*h Spirulina"* has lower total carbohydrates and available carbohydrates compared to the values reported by *Tătaru* and *Iatco (2024)* for the *"*Mini-baguette fortified with *Spirulina"* (Carbohydrates = 45.17%; Available carbohydrates = 41.42%).

Figures 3 and 4 present the mineral content of the product *"*Low-carb mini-baguette fortified with *Spirulina."*

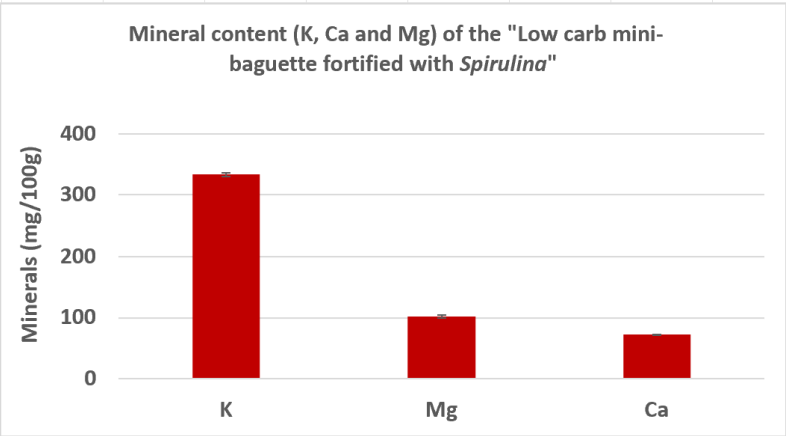

Fig. 3 - Mineral content (K, Ca and Mg) of the "Low carb mini-baguette fortified with *Spirulina*"

Among the minerals analyzed in the product *"*Low-carb mini-baguette fortified with *Spirulina,"* potassium showed the highest value: 333.27 mg/100 g. The potassium content of this mini-baguette is significantly higher compared to that reported by *Tătaru* and *Iatco (2024)* for the *"*Mini-baguette fortified with *Spirulina"* (K = 40.81 mg/100 g). Furthermore, the potassium content of the *"*Low-carb mini-baguette fortified with *Spirulina"* is 1.28 times higher than that reported by *Catană et al. (2022)* for the *"*Mini-baguette fortified with Jerusalem artichoke flour*"* (K = 260.85 mg/100 g).

The magnesium content of the product *"*Low-carb mini-baguette fortified with *Spirulina"* is comparable to that reported by *Catană et al. (2022)* for the *"*Mini-baguette fortified with Jerusalem artichoke flour*"* (Mg = 98.45 mg/100 g), whereas its calcium content is lower than that reported by the same authors (Ca = 145.21 mg/100 g).

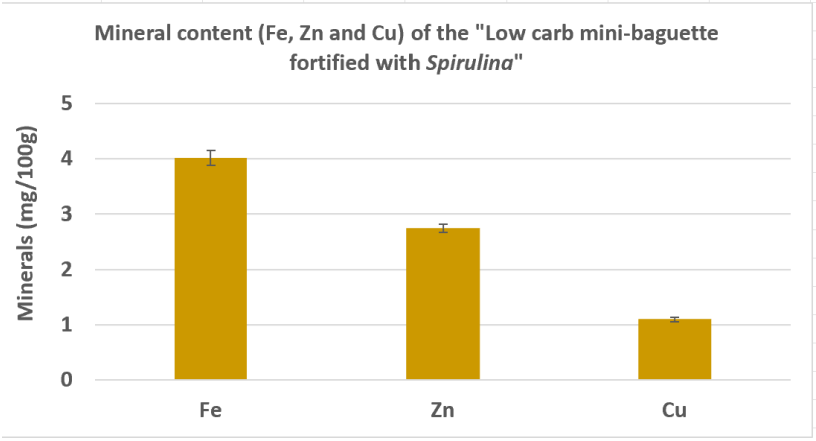

Fig. 4 - Mineral content (Fe, Zn and Cu) of the "Low carb mini-baguette fortified with *Spirulina*"

The iron content of the product *"*Low-carb mini-baguette fortified with *Spirulina"* is comparable to that reported by *Tătaru* and *Iatco (2024)* for the *"*Mini-baguette fortified with *Spirulina"* (Fe = 4.08 mg/100 g), while its zinc content is significantly higher than that reported by the same authors (Zn = 0.61 mg/100 g). The copper content of the low-carb mini-baguette fortified with *Spirulina* in this experimental study is the lowest among the minerals analyzed (Cu = 1.10 mg/100 g).

Due to the valuable ingredients used in its formulation, the product stands out for its total polyphenol content: 173.25 mg GAE/100 g. The total polyphenol content of this mini-baguette is 1.78 times higher than that reported by *Tătaru* and *Iatco (2024)* for the *"*Mini-baguette fortified with *Spirulina"* (Total polyphenols = 97.22 mg GAE/100 g).

Furthermore, the product *"*Low-carb mini-baguette fortified with *Spirulina"* exhibits an antioxidant capacity of 187.35 mg Trolox equivalents/100 g, higher than that reported by *Tătaru* and *Iatco (2024)* for the *"*Mini-baguette fortified with *Spirulina"* (Antioxidant capacity = 163 mg Trolox equivalents/100 g). Its antioxidant capacity is also higher compared to that reported by *Catană et al. (2022)* for the *"*Mini-baguette fortified with Jerusalem artichoke flour*"* (Antioxidant capacity = 135.67 mg Trolox equivalents/100 g).

The product *"*Low-carb mini-baguette fortified with *Spirulina"* is also notable for its total carotenoid content (Total carotenoids = 4.12 mg/100 g) and β-carotene content (β-carotene = 2.65 mg/100 g).

The microbiological indicators of the *"*Low-carb mini-baguette fortified with *Spirulina"* are presented in Table 2.

Table 2

Microbiological analysis of the "Low carb mini-baguette fortified with *Spirulina*"

Microbiological indicators	**"Low carb mini-baguette fortified with *Spirulina*"**
Yeast and mold (CFU/g)	< 10
Enterobacteriaceae (CFU/g)	< 10
Water activity	0.918

Following the microbiological analysis, it was found that the product "Low carb mini-baguette fortified with *Spirulina*" falls within the provisions of the legislation in force and presents low water activity values.

CONCLUSIONS

The product *"*Low-carb mini-baguette fortified with *Spirulina"* exhibits superior sensory qualities, high nutritional value, and notable antioxidant potential. This product has a low content of total carbohydrates (40,00%) and available carbohydrates (30.78%), a high content of protein (14.42%), ash (2.46%), minerals (K = 333.27 mg/100 g; Mg = 102.24 mg/100 g; Ca = 72.18 mg/100 g; Fe = 4.01 mg/100 g; Zn = 2.75 mg/100 g; Cu = 1.10 mg/100 g), and total dietary fiber (9.22%).

According to Regulation (EC) No. 1924/2006 of the European Parliament and of the Council, the *"*Low-carb mini-baguette fortified with *Spirulina"* can be considered a source of protein, as at least 12% of its energy value comes from protein (in this case, 21.36%), and a source of fiber, since its fiber content exceeds 6% (8.90%). Moreover, this mini-baguette is notable for its bioactive compound content (Total polyphenols = 173.25 mg GAE/100 g) and exhibits antioxidant capacity (187.35 mg Trolox equivalents/100 g).

Due to its complex biochemical composition, adapted to the metabolic needs of diabetic and obese patients, the product *"*Low-carb mini-baguette fortified with *Spirulina"* can be successfully incorporated into the diet of these patient groups.

ACKNOWLEDGEMENT

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RESEARCH ON THE USE OF BROCCOLI LEAVES TO OBTAIN A FUNCTIONAL INGREDIENT WITH HIGH NUTRITIONAL VALUE AND ANTIOXIDANT POTENTIAL

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CERCETĂRI PRIVIND VALORIFICAREA FRUNZELOR DE BROCCOLI, ÎN SCOPUL OBȚINERII UNUI INGREDIENT FUNCȚIONAL, CU VALOARE NUTRITIVĂ RIDICATĂ ȘI POTENȚIAL ANTIOXIDANT

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Keywords: *broccoli, leaves, functional ingredient, drying, hot air*

ABSTRACT

The agri-food industry can generate considerable amounts of waste, which may lead to serious environmental issues. Broccoli cultivation produces large quantities of waste (leaves, stems), which, due to their complex biochemical composition, can be valorized through the production of functional ingredients (powders). This study presents the results of research aimed at obtaining a functional ingredient (powder) by hot-air dehydration at 50°C and grinding of pretreated broccoli leaves derived from the cultivation of this vegetable species. The resulting functional ingredient is a green powder with characteristic taste and aroma. Biochemical analysis revealed that the powder obtained from processed broccoli leaves is notable for its content of glucosinolates (8.64–9.85 µmol/g d.w.), total polyphenols (8.94–9.33 mg GAE/g d.w.), vitamin C (62.47–74.85 mg/100 g), total carotenoids (111.24–132.10 mg/100 g), β-carotene (24.81–31.19 mg/100 g), lutein (47.83–57.75 mg/100 g), chlorophyll a (4.12–4.55 mg/g), and chlorophyll b (0.68–0.75 mg/g). Due to its high content of bioactive compounds, the functional ingredient derived from broccoli leaves exhibits antioxidant capacity ranging from 21.78 to 24.37 µmol TE/g.

REZUMAT

Industria agroalimentară poate genera cantități considerabile de deșeuri, ceea ce poate duce la probleme grave de mediu.Din cultura de broccoli, rezultă cantități mari de deșeuri (frunze, tulpini), care datorită compoziției biochimice complexe, pot fi valorificate, prin obținerea unor ingrediente funcționale (pulberi). În această lucrare sunt prezentate rezultatele cercetărilor întreprinse pentru obținerea unui ingredient funcțional (pulbere), prin deshidratarea cu aer cald la 50°C și măcinarea frunzelor de broccoli pretratate, rezultate din cultura acestei specii legumicole. Acest ingredient funcțional se prezintă sub forma unei pulberi verzi, care prezintă gust și miros, caracteristice. Analiza biochimică a evidențiat faptul că pulberea obținută din procesare frunzelor de broccoli, se remarcă prin conținutul în glucozinolați (8,64 µmol/g s.u.-9,85 µmol/g s.u.), polifenoli totali (8,94 mg GAE/g s.u.- 9,33 mg GAE/g s.u.), vitamina C (62,47 mg/100g-74,85mg/100g), carotenoizi totali (111,24mg/100g-132,10 mg/100g), β-Caroten (24,81mg/100g-31,19 mg/100g), luteină (47,83mg/100g- 57,75 mg/100g), clorofila a (4,12 mg/g-4,55mg/g), clorofila b (0,68mg/g-0,75mg/g). Datorită conținutului ridicat în compuși bioactivi, ingredientul funcțional obținut din frunzele de broccoli, prezintă capacitate antioxidantă (21,78 µmol TE/g- 24,37 µmol TE/g).

INTRODUCTION

Recently, food waste has become a popular topic of discussion, particularly regarding food security and climate change, due to its various negative effects and the increasing global awareness of the severity of the issue (*Mokrane et al., 2023*). The agri-food industry can generate considerable amounts of waste, which may lead to serious environmental problems *(Fernández et al., 2018).*

Broccoli (*Brassica oleracea* var. *italica*), a vegetable belonging to the cruciferous family (*Brassicaceae*), is rich in bioactive compounds that are beneficial for health, such as glucosinolates, phenolic compounds, vitamins C, B1, and E, carotenoids, and selenium (*Ali Redha et al., 2023*; *Borowski et al., 2008*). However, from agricultural production to distribution to consumers, cruciferous vegetables such as broccoli,

cabbage, and cauliflower generate by-products in the form of stems, leaves, and roots, which are considered waste during processing and are often discarded (*Shinali et al., 2024*).

The inflorescences, which are the edible parts of broccoli, account for less than 30% of the total mass, whereas the leaves and stems, representing over 70% of the remaining biomass, generate a substantial amount of waste after harvesting *(Zhang et al., 2017*). Broccoli by-products are typically treated as food waste, but broccoli leaves are particularly rich in bioactive compounds compared to other parts of the vegetable.

Broccoli leaves consist of two distinct parts - the blade and the petiole - each with different anatomical and physiological functions. Broccoli leaves have higher total polyphenol and flavonoid contents than the inflorescences and seeds, demonstrating that they can be a potential source of glucosinolates and have the highest contents of vitamins E and K, β-carotene, manganese, and calcium compared to the inflorescences and stems of broccoli (*Ares et al., 2014; Le et al., 2020; Liu et al., 2018*).

Catană et al. (2024) developed a functional ingredient in powder form by lyophilizing pretreated broccoli leaves at -55°C and subsequently grinding them. The "Functional ingredient from broccoli leaves (powder)" obtained by lyophilization exhibits high nutritional value and antioxidant potential. This functional ingredient is notable for its protein content, mineral elements (Na, K, Ca, Mg, Zn, Mn, and Fe), and bioactive compounds (total polyphenols, glucosinolates, vitamin C, β-carotene, lutein, chlorophyll a, and chlorophyll b). It qualifies as a source of protein (min. 29%), total fiber (min. 26%), potassium (min. 1300 mg/kg), iron (min. 4.35 mg/100 g), calcium (min. 2800 mg/100 g) and magnesium (min. 125 mg/100 g).

Furthermore, this functional ingredient stands out for its total content of polyphenols (min. 15.5 mg GAE/g dry matter), glucosinolates (min. 11.5 µmol/g dry matter), vitamin C (min. 125 mg/100 g), β-carotene (min. 28 mg/100 g), lutein (min. 60 mg/100 g), chlorophyll a (min. 5.5 mg/100 g), and chlorophyll b (min. 0.9 mg/g). Due to its high content of antioxidant compounds, the *"*Functional ingredient from broccoli leaves (powder)*"* exhibits antioxidant capacity of at least 55 µmol TE/g.

Catană et al. (2024) also developed a bakery product fortified with a functional ingredient (powder) obtained from cauliflower leaves. Thus, the product *"*Minicake fortified with cauliflower leaves powder*"* (fortification level 18%) stands out for its content of mineral elements (K = 234.93 mg/100 g; Ca = 62.25 mg/100 g; Mg = 29.74 mg/100 g; Fe = 2.75 mg/100 g; Zn = 1.16 mg/100 g), bioactive compounds (total polyphenols = 135.86 mg GAE/100 g; glucosinolates = 513.44 µmol/100 g; α-tocopherol = 0.656 mg/100 g; total carotenoids = 3.32 mg/100 g; β-carotene = 1.12 mg/100 g; chlorophyll a = 5.75 mg/100 g; chlorophyll b = 10.06 mg/100 g), and antioxidant capacity (3.02 mg TE/100 g).

In this study, the results of research aimed at obtaining a functional ingredient (powder) from pretreated broccoli leaves through hot-air dehydration and grinding, derived from the cultivation of this vegetable species, are presented.

MATERIALS AND METHODS

Waste (leaves) resulting from the conventional broccoli culture, from farmers in Dâmbovița county, were used in our experiments. Pretreated broccoli leaves (sorting, washing, boiling in water at 98-100°C for 2-3 minutes, cutting) were subjected to dehydration process in a in an electric dryer with forced convection (Memmert UFP 800, power de 4.8 kW), at temperature of 50°C, for 8-9 hours, up to a maximum humidity of 8%.

Fig. 1- Aspects of the technological process for obtaining of the "Functional ingredient from broccoli leaves (powder)"

Proba ID Proba IID Proba IIID

Fig. 2 - "Functional ingredient from broccoli leaves (powder)"

Milling of dried semi-finished products was performed by using Retsch mill (Knife Mill GRINDOMIX GM 200). Functional ingredient (powder) obtained from broccoli leaves was packed in hermetically sealed glass containers, protected with aluminum foil and kept in dry and cool spaces (at a maximum temperature of 20°C), until the sensory, biochemical and microbiological analyzes were performed .

For the qualitative characterisation of the “Functional ingredient from broccoli leaves (powder)” were used standardized methods and developed and validated methods in IBA Bucharest. Measurement of the color parameters of samples was performed at room temperature, using a CM-5 colorimeter (Konica Minolta, Japan), equipped with SpectraMagic NX software, to register CIELab parameters (L*, a*, b*).

The moisture content was determined according to the AACC 44-15A method. Protein content was determined by the Kjeldahl method with a conversion factor of nitrogen to protein of 6.25 (AOAC Method 979.09, 2005). Fat content was determined according to AOAC Method 963.15, and ash content according to AOAC Method 923.03 (AOAC, 2005). Total dietary fibre (TDF) was determined by enzymatic method using the assay kits: KTDFR ‘‘Total dietary fibre’’ (AOAC Method 991.43).

Determination of iron, manganese and zinc was performed by Inductively Coupled Plasma Mass Spectrometry (ICP-MS, model NexION300Q, Perkin Elmer) after dry digestion of the samples. The determination of sodium, potassium, calcium and magnesium was carried out by High-Resolution Continuum

Source Atomic Absorption Spectrometry (Analytik Jena, model contrAA 700 - High-Resolution Continuum Source Atomic Absorption Spectrometer), flame technique, after dry digestion of the samples.

Determination of the vitamin C was performed by high performance liquid chromatography coupled with mass spectrometry (*Catană et al., 2017*). Determination of β-carotene and all-trans lutein content was performed by high-performance liquid chromatography (HPLC-DAD) (*Catană et al., 2020*).

Total phenolic content was determined by Folin-Ciocalteu procedure, and antioxidant capacity by DPPH method (*Horszwald and Andlauer, 2011* with some modifications (concerning extraction media, time and mode of extraction, extract volumes of the used sample and reagents, using UV-VIS Jasco V 550 spectrophotometer). Determination of glycosinolate content was carried out using a rapid spectrophotometric method (*Mawlong et. al., 2017).* Determination of total carotenoids and chlorophyll a and b was carried out spectrophotometrically (*Chinnadurai et al., 2013*).

The water activity (Aw) was determined by the method ISO 21807:2004. Yeasts and molds were determined by the method SR ISO 21527-1:2009 and SR ISO 21527-2:2009. *Enterobacteriaceae* were determined according to the SR EN ISO 21528-2:2017 method and *Escherichia coli* by SR ISO 16649-2:2007 method. *Salmonella* was determined by the method SR EN ISO 6579-1:2017.

RESULTS

Following the sensory analysis, it was found that the functional ingredient from broccoli leaves is in the form of a powder with a characteristic taste and smell and dark green colour (Fig. 2). Following the instrumental color value, it was found that these powders recorded negative values of the color parameter a* and positive values of the luminance L* and the color parameter b* (Fig. 3).

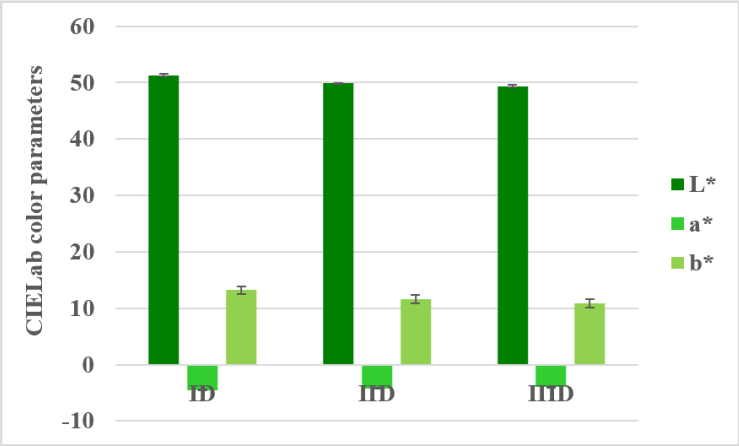

Fig. 3 - Color parameters of the "Functional ingredient from broccoli leaves (powder)"

Physico-chemical analysis revealed that the functional ingredient of broccoli leaves (powder) stands out for its content in protein, ash, total sugar and total fiber (Table 1).

Table 1

The physico-chemical indicators of the"Functional ingredient from broccoli leaves (powder)"

Physico-chemical indicators	"Functional ingredient from broccoli leaves (powder)"		
	Sample ID	Sample IID	Sample IIID
Moisture (%)	5.94±0.15	5.78±0.14	5.59±0.14
Ash (%)	10.87±0.16	11.95±0.18	13.85±0.21
Protein (%)	28.93±0.43	29.74±0.45	29.95±0.45
Fat (%)	6.48±0.09	6.61±0.09	6.73±0.09
Carbohydrates (%)	47.78±0.31	45.92±0.30	43.88±0.29
Available carbohydrates (%)	22.13±0.14	18.69±0.12	15.11±0.10
Total sugar (%)	4.53±0.07	4.84±0.07	5.03±0.08
Total fiber (%)	25.65±0.46	27.23±0.49	28.77±0.52
Energy value (kcal/100g)	314	308	298
Energy value (kJ/100g)	1313	1286	1245

The moisture content of the powder obtained from broccoli leaves (5.59-5.94%) is higher than that reported by *Betoret* and *Rosell (2020) f*or this functional ingredient (Moisture = 3.69–4.1%). The total ash content of the broccoli leaf powders in this experimental study (Ash = 10.87-13.85%) is higher compared to the value reported by *Drabińska (2018)* (10.65%). Furthermore, the powders obtained from broccoli leaves are an important source of protein, with protein content (Protein = 28.93-29.95%) comparable to that reported by Drabińska *et al.* (2018) (Protein = 28.99%). The lipid content of the broccoli leaf powders (Lipids =6.48-6.73%) is comparable to that reported for this powder by *Yan et al. (2023)* (Lipids = 6.72%). Additionally, the total fiber content of the powders obtained from broccoli leaves (Total fiber = 25.65-28.77%) is similar to that reported by *Berndtsson et al.* (2020) (Fiber = 26–32%).

The "Functional ingredient from broccoli leaves (powder)" stands out for its content in mineral elements (fig. 4, 5 and 6). Among the determined mineral elements, in the case of the "Functional ingredient from broccoli leaves (powder)", potassium it recorded the highest content (Fig. 4).

The potassium content of the powder obtained from broccoli leaves ranged between 12,800.15 and 14,200.55 mg/100 g. The potassium content of the powders obtained from the leaves is comparable to that reported by *Liu et al. (2018)* for broccoli leaves: K = 13600 mg/100g d.w. Potassium, as a predominant intracellular cation, has been considered to be pivotal in multiple physiological processes related to human health *(Minà et al., 2020).* Abnormal blood potassium levels are associated with an increased risk of cardiometabolic diseases and mortality in the general population (*Fan et al., 2024*).

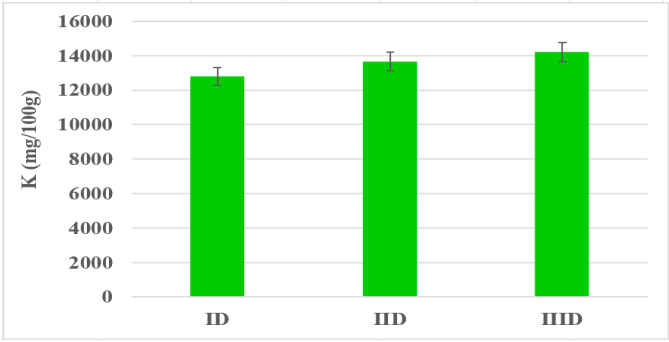

Fig. 4 - Potassium content of the "Functional ingredient from broccoli leaves (powder)"

At the same time, according to our results, the "Functional ingredient from broccoli leaves (powder)", can be considered an important source of calcium and magnesium. Calcium and magnesium are two mineral elements with an important role in the human body. Calcium and magnesium affect muscle mass and function and are important for optimal vitamin D status (*Hibler et al., 2020*). Insufficient dietary intake of nutrients such as calcium and magnesium can be associated with increased risk of cancer, cardiovascular diseases, metabolic diseases and mortality (*Schwingshack*l *et al., 2015*; *Asemi et al., 2015*).

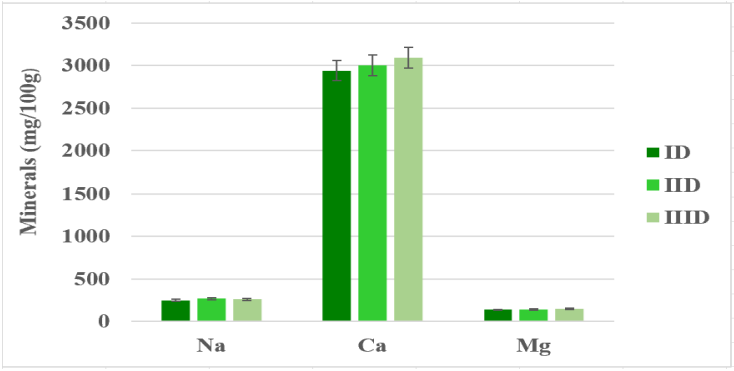

Fig. 5 - Mineral content (Na, Ca, Mg) of the "Functional ingredient from broccoli leaves (powder)"

The content in Zn, Mn and Fe of the "Functional ingredient from broccoli leaves (powder)", recorded lower values, compared to other determined mineral elements, being in the range of 2.36-4.69 mg/100g.

The contents of Zn, Mn, and Fe in the *"*Functional ingredient from broccoli leaves (powder)*"* are comparable to those reported by *Liu et al. (2018)* for powders obtained from broccoli waste: Zn = 2.33 mg/100 g; Mn = 0.70 mg/100 g; Fe = 4.05 mg/100 g. According to the results obtained in this study, among Zn, Mn, and Fe, the iron content in the broccoli leaf powder is the highest. Iron is a micronutrient which plays important structural and functional roles in all organisms. Iron plays a vital role in oxygen mobilization and is one of the major constituents of oxygen carriers; hemoglobin and myoglobin, heme-containing enzymes, and non-heme proteins. Moreover, iron is involved in the critical functions such as oxygen sensing, detoxification of xenobiotics, and oxidative phosphorylation (*Samarakoon et al.*, 2023).

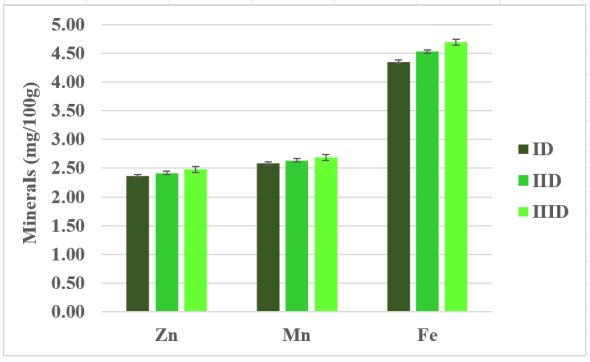

Fig. 6 - Mineral content (Zn, Mn, Fe) of the "Functional ingredient from broccoli leaves (powder)"

It is worth noting that the "Functional ingredient from broccoli leaves (powder)" is an important source of bioactive compounds: total polyphenols, glucosinolates, vitamin C, β-Carotene, lutein, chlorophyll a, chlorophyll b (Table 2).

Table 2

Bioactive compounds content of the"Functional ingredient from broccoli leaves (powder)"

Bioactive compounds	"Functional ingredient from broccoli leaves (powder)"		
	Sample ID	Sample IID	Sample IIID
Total polyphenols (mg GAE/g d.w.)	9.33±0.23	8.75±0.22	8.94±0.22
Glucosinolates (µmol /g dw.)	9.85±0.25	8.64±0.22	8.98±0.22
Vitamin C (mg/100g)	74.85±2.25	62.47±1.87	69.67±1.74
Total carotenoids (mg/100g)	111.24±1.11	123.63±1.24	132.10±1.32
β- Carotene (mg/100g)	24.81±0.55	28.93±0.64	31.19±0.68
Lutein (mg/100g)	47.83±1.10	53.78±1.24	57.75±1.33
Chlorophyll a (mg/g)	4.55±0.05	4.12±0.04	4.18±0.04
Chlorophyll b (mg/g)	0.75±0.007	0.68±0.007	0.70±0.007

The total polyphenol content of the powders obtained from broccoli leaves in this experimental study, using hot air drying, ranged between 8.75 and 9.33 mg GAE/g d.w., being comparable to that reported by *Drabińska et al. (2018)* for broccoli leaf powder (9.56 mg/g d.w.). At the same time, the total polyphenol content of this functional ingredient is 1.63–1.74 times higher compared to that reported by *Tukassar et al. (2023)* for cauliflower by-products powder (537.40 mg GAE/100 g).

Polyphenols play a vital role in protecting the body against external stimuli and in eliminating reactive oxygen species (ROS), which are implicated in the development of several diseases. Dietary polyphenols also contribute to improving lipid profiles, blood pressure, insulin resistance, and systemic inflammation (*Rana et al., 2022*).

Glucosinolates are key bioactive compounds in the functional ingredient (powder) obtained from broccoli leaves. These compounds are highly valuable for health, providing protection against serious diseases such as colorectal cancer, prostate cancer, breast cancer, and myocardial infarction (*Akram et al., 2021*). The glucosinolate content of the powders obtained from broccoli leaves is 1.79–2.04 times higher than that reported by *Drabińska et al. (2018)* for broccoli leaf powder (Glucosinolates = 4.84 µmol/g dw.).

The vitamin C and lutein content of the "Functional ingredient from broccoli leaves (powder)" is lower compared to that reported by *Catană et al.* (2023) for powder obtained from cauliflower leaves: vitamin C = 76.50–89.44 mg/100 g; lutein = 11.65–14.87 mg/100 g. Similarly, the β-carotene content of this functional ingredient is lower than that reported by *Catană et al. (2023)* for cauliflower leaf powder: β-carotene = 39.45–47.21 mg/100 g. Dietary intake and tissue levels of carotenoids have been associated with a reduced risk of several chronic diseases, including cardiovascular diseases, type 2 diabetes, obesity, brain-related diseases and some types of cancer. However, intervention trials with isolated carotenoid supplements have mostly failed to confirm the postulated health benefits *(Bohn et al., 2021).*

Due to the high content of antioxidants (β-carotene, vitamin C, vitamin E, total polyphenols, etc.) the "Functional ingredient from broccoli leaves (powder)", shows antioxidant capacity: Sample ID= 21.78 µmol TE/g; Sample IID = 22.91 µmol TE/g; Sample IIID = 24.37 µmol TE/g.

Following the microbiological analysis, it was found that the "Functional ingredient from broccoli leaves (powder)" falls within the provisions of the legislation in force and presents low water activity values (Table 3).

Table 3

Microbiological analysis of the"Functional ingredient from broccoli leaves (powder)"

Microbiological indicators	"Functional ingredient from cauliflower leaves (powder)"		
	Sample ID	Sample IID	Sample IIID
Yeast and mold (CFU/g)	< 10	< 10	< 10
Enterobacteriaceae (CFU/g)	< 10	< 10	< 10
Escherichia coli (CFU/g)	< 10	< 10	< 10
Salmonella (in 25 g)	Absent	Absent	Absent
Water activity	0.170	0.167	0.160

CONCLUSIONS

The "Functional ingredient from broccoli leaves (powder)" obtained by lyophilization has high nutritional value and antioxidant potential. Thus, this functional ingredient stands out for its protein content, mineral elements (Na, K, Ca, Mg, Zn, Mn and Fe) and bioactive compounds (total polyphenols, glucosinolates, vitamin C, β-Carotene, lutein, chlorophyll a, chlorophyll b).

The "Functional ingredient from broccoli leaves (powder)" is a source of protein (min. 28.5%), total fiber (min. 25.5 %), K (min. 1250 mg/kg), Fe (min. 4.25 mg/100g), Ca (min. 2900 mg/100g), Mg (min. 130 mg/100g). At the same time, this functional ingredient stands out for its total content of polyphenols (min. 8.5 mg GAE/g d.w.), glucosinolates (min. 8.5 µmol /g d.w.), vitamin C (min. 60 mg/100g), β-Carotene (min. 24 mg/100g), lutein (min. 45 mg/100g), chlorophyll a (min. 4.0 mg/100g) and chlorophyll b (min. 0.60 mg/g) .

Due to the high antioxidant content, the "Functional ingredient from broccoli leaves (powder)" has antioxidant capacity (min. 21.5 µmol TE/g).

Due to nutritional qualities and antioxidant capacity, the "Functional ingredient from broccoli leaves (powder)" can be used for fortification of conventional and gluten-free bakery and pastry products.

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RESEARCH ON THE INFLUENCE OF TECHNOLOGICAL FACTORS ON FRUIT PRODUCTION IN PIMPINELLA ANISUM (ANISE) SPECIES

CERCETĂRI PRIVIND INFLUENȚA FACTORILOR TEHNOLOGICI ASUPRA PRODUCȚIEI DE FRUCTE LA SPECIA PIMPINELLA ANISUM (ANASON)

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Keywords: *anise, distance, epoch of sowing*

ABSTRACT

This paper presents data on the influence of technological sequences on the species Pimpinella anisum cultivated under the conditions of A.R.D.S. Secuieni in the period 2023-2024. The average fruit production was between 382 kg/ha in the third epoch of sowing and 659 kg/ha in the first period. The average fruit production per hectare ranged between 526 kg/ha in the control variant (25 cm between rows x continuous row) and 675 kg/ha in the variant sown at 50 cm between rows and 15 cm between plants/row.

REZUMAT

În lucrarea de faţă se prezintă date privind influența unor secvențe tehnologice la specia Pimpinella anisum cultivată în condiţiile de la S.C.D.A. Secuieni în perioada 2023-2024. Producţia medie de fructe a fost cuprinsă între 382 kg/ha la epoca a III-a şi 659 kg/ha la epoca I-a. Producţia medie de fructe la hectar a oscilat între 526 kg/ha la varianta martor (25 cm între rânduri x rând continuu) şi 675 kg/ha la varianta semănată la 70 cm între rânduri şi 15 cm între plante/rând.

INTRODUCTION

Anise (*Pimpinella anisum* L.) is an annual spice and medicinal plant belonging to the family Apiaceae and native to Mediterranean region. Today, anise fruits are an important natural raw material, which is used in the pharmaceutical, perfumery, food and cosmetic industries. Recently, this spice plant has attained more attention of consumers due to the antimicrobial, antifungal, insecticidal, and antioxidative effects on human health (*Gulcin et al, 2003; Knio et al., 2008; Tepe et al, 2006; Ahmed et al, 2021; El-Saadony et al, 2025*).

The drug as well as the essential oil is characterised by carminative, mild expectorant, diuretic, antiseptic and antispasmodic properties. Anise fruits contain around 1.5 to 5.0% essential oil mainly composed of volatile phenylpropanoids like trans-anethole (more than 90% of the total essential oil content) followed by γ-himachalene, methyl chavicol (estragol), anisaldehyde, β-himachalene and α-zingiberene (*Orav et al, 2008; Tabanca et al, 2005; Yan et al. 2011*).

The yield of aniseed may noticeably vary depending on ecological conditions such as temperature, precipitation and soil fertility. Previous studies showed the effects of row spacing, water supply, fertilization, sowing time, sowing density on anise seed yield and quality were studied under field and greenhouse conditions (*Awad et al., 2005; Tuncturk and Yildirim, 2006*; *Habib, 2014; Nimet, 2015*).

Research reported that delaying the sowing date resulted in decreased plant height and seed yield of anise (İpek et al., 2004; Al-Awak, 2010).

Tunçtürk and Yıldırım (2006) reported that the number of branches and umbrels decreased with narrower sowing of anise. Meena et al. (2012) stated that sowing at 20 × 10 cm could be the optimum row space for higher productivity in anise.

Delayed sowing under warmer conditions in spring may lead to shortening of the growing cycle, which decreases the amount of UV radiation intercepted by the crops and may reduce the formation of reproductive organs. Delayed sowing results in reduced vegetative growth and immediate response to

photoperiod, which leads to reduced plant length and number of umbels and decreased fruit yield (*Zolleh et al., 2009; Mirshekari et al., 2011; Habib, 2015*).

The purpose of this work was to introduce this species into the culture in order to develop the cultivation technology.

MATERIALS AND METHODS

The researches were carried between 2023 and 2024 at A.R.D.S. Secuieni on a typical cambic soil type. Characterized as being well supplied with mobile phosphorus (39 ppm - P2O5), moderately supplied in nitrogen with the soil nitrogen index of 2.1, well supplied in mobile potassium (161 ppm - K2O), slightly acidic, with the pH (in aqueous suspension) of 6.29 and a humus content of 2.3%.

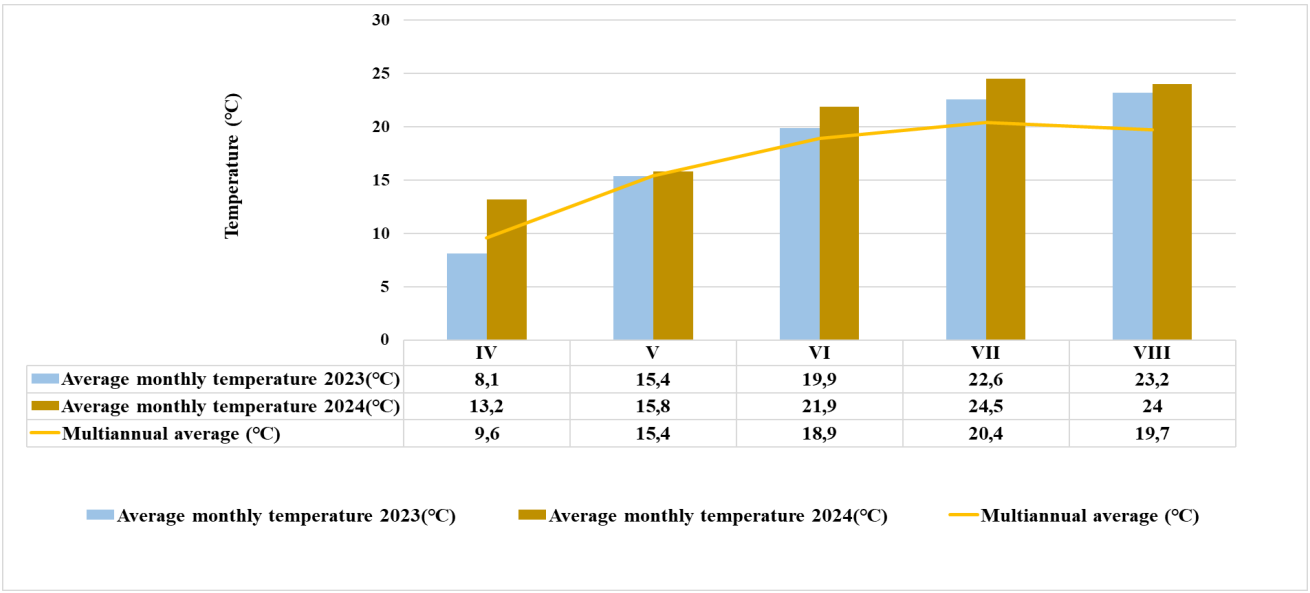
In the conditions of A.R.D.S. Secuieni we experimented four sowing epochs: V1 (control) - Epoch I, sowing in the first decade of April); V2 - Epoch II, sowing in the second decade of April); V3 - Epoch III, sowing the third decade of April).

At *Pimpinella anisum* species, the aim was to establish a technological link through the establishment of the optimal nutritional space in a bifactorial experience according to the subdivided parcel method in three repetitions.

Experienced factors are: A - the distance between rows with graduations: a1 – 12.5 cm, a2 - 25 cm and a3 - 50 cm and B - the distance between plants per row with graduations: continuous row, b2 - 10 cm and b3 - 15 cm.

The soil work and the preparation of the germination bed consisted in releasing the soil from the plant debris in the pre-planting. Stubble - turning and plowing at a depth of 30 cm. In spring preparation of the germination bed was made with a harrow disc and the sowing was done manually at a depth of 1 cm. In spring preparation of the germination bed was made with a harrow disc and the sowing was done manually at a depth of 1 - 2 cm.

The 2022/2023 agricultural year is characterized as a warm and very dry one. In terms of temperatures, the monthly averages were higher than the multiannual monthly averages, except for April, when the monthly average temperature was lower than the multiannual average by -1.5° C (figure 1 and 2).



	IV	V	VI	VII	VIII
Average monthly temperature 2023(°C)	8,1	15,4	19,9	22,6	23,2
Average monthly temperature 2024(°C)	13,2	15,8	21,9	24,5	24
Multiannual average (°C)	9,6	15,4	18,9	20,4	19,7

Fig. 1 - Temperatures recorded during the anise growing season in the period 2023-2024

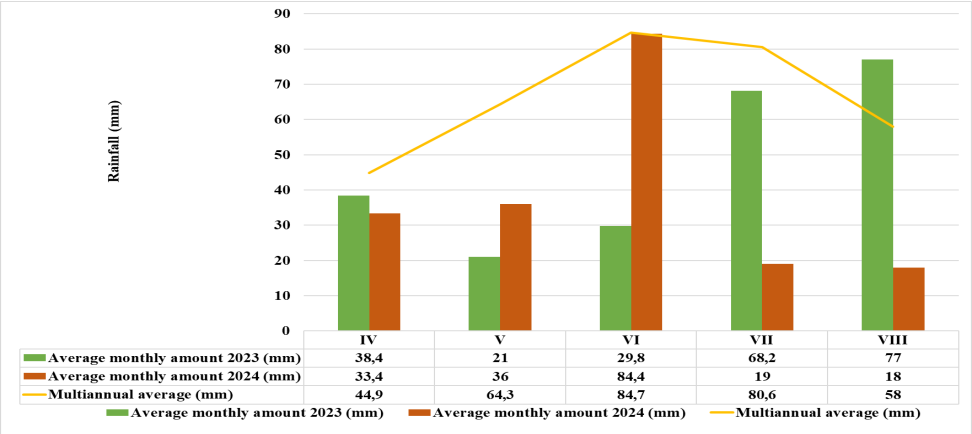


Fig. 2 - Precipitation recorded during the anise growing season in the period 2023-2024

The 2023-2024 agricultural year was hot and dry. June was hot, with average temperatures above 20-22℃, compared to the multiannual average of 18.9℃. July was extremely hot, with the monthly average temperature being 24.5℃, 4℃ above the multiannual average of 20.4℃. August was characterized from a thermal point of view as extremely hot, with the average temperature being 24℃ compared to the multiannual average of 19.7℃, which means that the average temperature increased by 4.3℃. In terms of precipitation, the April - August period recorded monthly deviations from the multiannual monthly amount ranging between - 28.3 mm (May) and 61.6 mm (July) (figure 1 and 2).

RESULTS

The average number of branches/plant varied from 5.4 at the 3rd sowing period to 6.5 at the 1st sowing period (control of the experiment). The average fruit weight per plant ranged between 0.96 g at the 3rd sowing period and 1.81 g at the 1st planting period. Statistically assured negative production differences were between 0.62 g and 0.85 g at the sowing periods of the 2nd and 3rd decade of April (table 1).

Table 1

The number of branches per plant and the weight of fruit/plant obtained from anise depending on the sowing season in the period 2023-2024

Variant	Number of branches/plant				Fruit weight/plant (g)			
	Kg/ha	%	Diff. (Kg/ha)	Sign.	Kg/ha	%	Diff. (Kg/ha)	Sign.
V1	6.5	100	Ct.		1.81	100	Ct.	
V2	6.6	101.54	0,1		1.19	65.74	-0.62	oo
V3	5.4	83.08	-1.1	ooo	0.96	53.03	-0.85	ooo
	LSD 5% - 0.05 LSD 1% - 0.23 LSD 0.1% - 0.56				LSD 5% - 0.13 LSD 1% - 0,37 LSD 0.1% - 0.72			

Table 2

The fruit production obtained from anise in the period 2023-2024

Variant	Average fruit production (kg/ha)			
	Kg/ha	%	Diff. (kg/ha)	Sign.
V1	659	100	Ct.	
V2	442	67.07	-217	ooo
V3	382	57.96	-277	ooo
	LSD 5% - 55 kg/ha LSD 1% - 114 kg/ha LSD 0.1% - 208 kg/ha			

The average fruit production ranged between 382 kg/ha in the third epoch of sowing and 651 kg/ha in the first epoch of sowing (control). Compared to the control, statistically significant and very significant negative assured production deficits were obtained in the variant sown in the second period of 217 kg/ha and in the third period of 277 kg/ha (table 2).

The interaction of the studied factors influenced the average fruit production of the anise species. Compared to the control variant a1xb1 (526 kg/ha), production increases were obtained in all experimental variants ranging from 39 to 149 kg/ha, being statistically assured and interpreted as significant, distinctly positive and highly significant (table 3).

The average weight of fruit/plant was influenced by the interaction of the studied factors (row spacing and plant spacing per row). Compared to the control variant a1xb1 (1.09 g), positive differences were achieved at all experimental variants ranging from 0.37 to 0.85 (table 4).

The number of branches ranged between 7.2 in the control variant and 9.6 in the variant planted at 50 cm between rows and 15 cm between plants/row (table 5).

Table 3

The influence of the interaction between the distance between rows and the distance between plants per row on the average of fruit production at anise in the period 2023-2024

Distance between rows (A)	Distance between plants / row (B)	Average fruit production (kg/ha)	%	Diff.	Sign.
a1-12.5 cm	b1-continous row	526	100	Ct.	
	b2-10 cm	548	104.18	22	
	b3-15 cm	579	110.08	53	**
a2-25 cm	b1-continous row	535	101.71	9	
	b2-10 cm	566	107.41	39	*
	b3-15 cm	589	111.98	63	**
a3-50 cm	b1-continous row	601	114.26	75	**
	b2-10 cm	630	119.77	104	***
	b3-15 cm	675	128.33	149	***
LSD 5% - 23 kg/ha LDS 1% - 46 kg/ha LSD 0.1% - 84 kg/ha					

Table 4

The influence of the interaction between the distance between rows and the distance between plants per row on the average fruit weight/plant at anise in the period 2023-2024

Distance between rows (A)	Distance between plants / row (B)	Fruit weight/plant (g)	%	Diff.	Sign.
a1-12.5 cm	b1-continous row	1,09	100	Mt.	
	b2-10 cm	1,46	133,94	0,37	*
	b3-15 cm	1,68	154,13	0,59	**
a2-25 cm	b1-continous row	1,29	118,35	0,2	*
	b2-10 cm	1,39	127,52	0,3	*
	b3-15 cm	1,67	153,21	0,58	**
a3-50 cm	b1-continous row	0,91	83,49	-0,18	
	b2-10 cm	1,61	147,71	0,52	**
	b3-15 cm	1,94	177,98	0,85	**
LSD5% - 0.19 g LSD1% - 0.43 g LSD 0.1% - 0.94 g					

Table 5

The influence of the interaction between the distance between rows and the distance between plants per row on the number of branches/plant at anise in the period 2023-2024

Distance between rows (A)	Distance between plants / row (B)	Number of branches/ plant	%	Diff.	Sign.
a1-12.5 cm	b1-continous row	7,2	100	Mt.	
	b2-10 cm	7,7	106,94	0,5	*
	b3-15 cm	8,2	113,89	1	**
a2-25 cm	b1-continous row	8,2	113,89	1	**
	b2-10 cm	8,9	123,61	1,7	***
	b3-15 cm	8	111,11	0,8	*
a3-50 cm	b1-continous row	8,1	112,50	0,9	*
	b2-10 cm	9	125,00	1,8	***
	b3-15 cm	9,6	133,33	2,4	***
LSD5% - 0.43 LSD1% - 0.93 LSD 0,1% - 1.48					

CONCLUSIONS

Anise is a highly valued herb and spice known for its distinct licorice flavor, containing potent compounds like anethole that aid digestion, reduce bloating, and soothe respiratory issues.

In the present study, fruit production is influenced by the sowing time and the interaction of the studied factors, with the highest production recorded for the variant sown in the first decade of April and at a distance of 50 cm between rows and 15 cm distance between plants/row.

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RESEARCH ON THE BEHAVIOR OF SOME PERENNIAL GRASS AND LEGUME SPECIES GROWN IN SIMPLE MIXTURES IN THE PEDOCLIMATIC CONDITIONS OF A.R.D.S. SECUIENI

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CERCETĂRI PRIVIND COMPORTAREA UNOR SPECII DE GRAMINEE ȘI LEGUMINOASE PERENE CULTIVATE ÎN AMESTECURI SIMPLE ÎN CONDIȚIILE PEDOCLIMATICE DE LA S.C.D.A. SECUIENI

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Keywords: *grasses, legumes, simple mixtures, production*

ABSTRACT

The research was carried out at A.R.D.S. Secuieni, a unit located in the SE part of Neamț County, during the period 2023/2025, with the aim of analyzing the competitiveness of the species Onobrychis viciifolia Scop. and Bromus inermis Leyss cultivated alone or in simple mixtures, under different fertilization conditions with complex mineral fertilizers. During the analyzed period, the weather conditions were very different, which influenced the forage production obtained. The average dry matter production varied within very wide limits from 5.1 t/ha dry matter as obtained in the variant sown with Bromus inermis 100% and fertilized with complex fertilizer 30:30:30 and up to 13.6 t/ha dry matter as obtained in the variant sown with the mixture Bromus inermis Leyss. (25%) + Onobrychis viciifolia Scop. (75%) and fertilized with complex fertilizer 50:50:50.

REZUMAT

Cercetările s-au efectuat la S.C.D.A. Secuieni, unitate situată în partea S-E a județul Neamț, în perioada 2023/2024, cu scopul de a analiza competitivitatea speciilor Onobrychis viciifolia Scop. și Bromus inermis Leyss cultivate singure sau în amestecuri simple, în diferite condiții de fertilizare cu îngrășăminte minerale complexe. În perioada analizată, condițiile meteo au fost foarte diferite, ceea ce a influențat producția de furaje obținută. Producția medie de substanță uscată a variat în limite foarte largi de la 5,1 t/ha substanță uscată cât s-a obținut în vaianta semănată cu Bromus inermis 100% și fertilizată cu îngrășământ complex 30:30:30 și până la 13,6 t/ha substanță uscată cât s-a obținut în varianta semănată cu amestecul Bromus inermis Leyss. (25%) + Onobrychis viciifolia Scop. (75%) și fertilizată cu îngrășământ complex 50:50:50.

INTRODUCTION

Given the increasing demands on the resistance of forage production to climatic fluctuations, the optimization of technological solutions becomes an important research direction. Overseeding of degraded grasslands and the establishment of sown grasslands is possible only by applying a complex of technological measures, where the choice of resistant species and varieties is an important element in order to obtain high and quality forage production *(Golinski P. 2008).*

Many researchers have studied sown meadows, developing recommendations for the cultivation of perennial forage plants. These include the proportions of grasses and perennial legumes in forage mixtures, the application of growth stimulants, and the modification of mowing schedules depending on the weather conditions of a particular growing season *(Samuil C., 2010; Carlsson G., 2008).* Such an adaptive strategy contributes to the stabilization of productivity and the maintenance of the qualitative composition of green biomass under conditions of climatic stress *(Saltanat B., 2025).*

The composition and nutritional value of feeds are extremely varied, both between feed types and within a given feed type, depending on a variety of factors *(Wilkins R.J., 2000).*

Legumes have a higher protein content, grasses compensate with their carbohydrate content, and legumes benefit from nitrogen fixation when grown together. Therefore, mixtures of grasses and perennial legumes can be more productive than when one species is grown in a monoculture system *(Albayrak S., et al. 2013, Naie M., et al. 2023)*. Sparcet has excellent drought tolerance due to a deep and extensive root system *(Chorley P., 1981; Goplen et al. 1991; Barnes et al. 2003*) and will persist in drought conditions, but is not recommended for areas with annual rainfall less than 300 mm due to reduced green mass and dry matter production.

Also, the non-arrested brome usually grows in temperate regions with annual rainfall greater than 330 mm *(Ellis-Felege S.N., 2013; Sedivec K., 1997).* The ability to withstand dry environments makes this species a valuable pasture forage crop in arid temperate regions *(Otfinowski R., 2007)*. Previous studies have indicated a direct correlation between nitrogen input and dry matter yields. *(Vinton M.A., et al 2006; Levang-Brilz, N., et al, 2003; DiAllesandro, A., et al, 2013)*, so the productivity, dominance and invasiveness of bromus species increase with increasing available nitrogen in the soil *(Gerry, A.K., et al, 1997; Leyshon, A.J., et al 1995)*.

Micronutrient fertilization helps to improve the chemical composition of forages and the floristic structure. Prevention of micronutrient deficiencies in forages is achieved by fertilization with organic or mineral fertilizers with microelements *(Ryser J.P. et al, 2001).* The quality of forages depends on the nutritional value (potential to provide nutrients, digestibility and their content), the amount of forage consumed and the presence of elements that degrade quality *(Ball D. et al, 2001).* In the present work, the objective of the research was to present technological parameters such as the influence of some species of perennial grasses and legumes but also of fertilization on forage production.

MATERIALS AND METHODS

The research was conducted at the Secuieni Agricultural Research and Development Station, in the agricultural years 2023/2025. The experiment was established in the spring of 2023 and was located according to the two-factor subdivided plot method, being of the AxB type, in three repetitions.

The studied factors were: A - species and simple mixtures of species (perennial grasses and legumes) with five graduations: a_1 - 100% grasses (100% *Bromus inermis* L.); a_2 - 75% grasses (75% *Bromus inermis* L.) + 25% legume (25% *Onobrychis viciifolia* L.); a_3 - 50% grasses (50% *Bromus inermis* L.) + 50% legume (50% *Onobrychis viciifolia* L.); a_4 - 25% grasses (25% *Bromus inermis* L.) + 75% legume (75% *Onobrychis viciifolia* L.); a_5 -100% legume (100% *Onobrychis viciifolia* L.); B - fertilization with three graduations: b_1 - $N_0P_0K_0$; b_2 - $N_{30}P_{30}K_{30}$; b_3 - $N_{50}P_{50}K_{50}$. Sowing was done with the U650 tractor in conjunction with the Haldrup experimental field seeder (Figure 1).

Fig. 1 - Placement of experience in the field

The soil type is a typical cambic phaeozem (chernozem) with medium texture and neutral (pHH2O – 7.26). The soil on which the experiment was located was characterized as being well supplied in active humus (2.33%), very well supplied in phosphorus (189 mg/kg), potassium (304 mg/kg), excessively supplied in Mg (253 mg/kg) and Mn (369 mg/kg), poorly supplied in nitrogen (9.4 mg/kg N – NO3) and Zn (1 mg/kg). The sown area of the experimental plot was 12 m2, of which 10 m2 were harvested. During the study years, three production cuts were made in the phenophase of grasses heading and legumes budding.

Fertilization was done manually with the Easy Drop device in the first year during land preparation, and from the second year, mineral fertilizers were administered when the plants started to grow (Figure 2).

Fig. 2 - Administration of complex fertilizers in the experimental field

Harvesting was done at a height of 4-5 centimeters from the ground using the BCS 615 lawn mower.

RESULTS

The influence of fertilization on forage production, under the conditions at A.R.D.S. Secuieni, was highlighted by comparing the dry matter production of the variant without fertilization with the production achieved in the variants fertilized with different doses of fertilizer.

Analyzing the separate influence of the species and simple mixtures of species, it is found that the forage production had values ranging between 15.76 t/ha d.m. as obtained in the variant sown with the species *Bromus inermis* 100% and 26.84 t/ha d.m. as obtained in the variant sown with the mixture *Bromus inermis* L. 25% + *Onobrychis viciifolia* L. 75%.

Compared to the control variant (*Bromus inermis* L. 100%), all production increases in the studied mixtures were statistically ensured as being highly significant except for the mixture formed by *Bromus inermis* L. 75% + *Onobrychis viciifolia* L. 25% (table 1).

Table 1

Influence between species and simple species mixtures on dry matter production, at scythe I, in the period 2023-2025

Variant	D.m. production	Difference		Signif.
	t/ha	t/ha	%	
a_1 - B.i. (100%) (ct.)	15,76	-	100	Control
a_2 - B.i. (75%) + O.v. (25%)	19,46	3,70	123,5	
a_3 - B.i. (50%) + O.v. (50%)	24,13	8,37	153,1	***
a_4 - B.i. (25%) + O.v. (75%)	26,84	11,08	170,3	***
a_5 - O.v. (100%)	24,78	9,02	157,2	***
	DL 5%	3,82		
	DL 1%	5,71		
	DL 0,1%	7,22		

Analyzing the influence of fertilization on the average dry matter production, under the conditions at A.R.D.S. Secuieni, it is observed that fertilization with complex fertilizers led to obtaining high dry matter productions, ranging between 16.12 t/ha d.m. in the control variant and 20.04 t/ha d.m. in the variant fertilized with $N_{30}P_{30}K_{30}$, with a significant increase in production compared to the control variant, the differences being 2.20 t/ha d.m. and 3.92 t/ha d.m. (table 2).

Table 2

Influence of fertilization on dry matter production, in class I, in the period 2023-2025

Variant	D.m. production	Difference		Signif.
	t/ha	t/ha	%	
b_1 - nefertilizat (ct.)	16,12	-	100	Control
b_2 - $N_{30}P_{30}K_{30}$	20,04	3,92	124,3	*
b_3 - $N_{50}P_{50}K_{50}$	18,32	2,20	113,6	
	DL 5%	2,63		
	DL 1%	4,37		
	DL 0,1%	8,15		

From the analysis of the results obtained, it is observed that in the case of the influence of the cultivated species or mixture on the dry matter production, at the second mowing, the productions obtained ranged between 6.48 t/ha d.m. as obtained in the variant sown with *Bromus inermis* L. 100% (control) and up to 11.48 t/ha d.m. as obtained in the variant sown with the Onobrychis viciifolia species 100%. With the exception of the variant sown with the mixture formed by *Bromus inermis* L. 25% + *Onobrychis viciifolia* L. 75%, in all other variants statistically assured production increases were obtained and interpreted as being very significant (Table 3).

Table 3

The influence between species and simple species mixtures on dry matter production, at the second mowing, in the period 2023-2025

Variant	D.m. production	Difference		Signif.
	t/ha	t/ha	%	
a_1 - B.i. (100%) (ct.)	6,48	-	100	Control
a_2 - B.i. (75%) + O.v. (25%)	7,99	1,51	123,3	
a_3 - B.i. (50%) + O.v. (50%)	9,90	3,42	152,8	***
a_4 - B.i. (25%) + O.v. (75%)	11,08	4,60	171,0	***
a_5 - O.v. (100%)	11,48	5,00	177,2	***
	DL 5% =	1,76		
	DL 1% =	2,37		
	DL 0,1% =	3,16		

Following the research conducted, the results obtained in the second harvest showed that dry matter production ranged between 6.39 t/ha d.m. in the unfertilized variant and 7.74 t/ha d.m. in the variant fertilized with $N_{50}P_{50}K_{50}$ (Table 4).

Table 4

The influence of fertilization on dry matter production, at scythe II, in the period 2023-2025

Variant	D.m. production	Difference		Signif.
	t/ha	t/ha	%	
b_1 - nefertilizat (ct.)	6,39	-	100	Control
b_2 - $N_{30}P_{30}K_{30}$	7,49	1,10	117,3	
b_3 - $N_{50}P_{50}K_{50}$	7,74	1,35	121,1	
	DL 5% =	1,36		
	DL 1% =	2,25		
	DL 0,1% =	4,21		

At the third mowing, the results obtained showed that the highest value of the dry matter production was obtained in the variant sown with the mixture formed by *Bromus inermis* 25% + *Onobrychis viciifolia* 75%, of 9.70 t/ha dry matter. Compared to the control variant, this achieved very significant production increases. The lowest production was obtained in the variant sown with the species *Bromus inermis* 100%, of 7.0 t/ha dry matter. (Table 5).

Table 5

The influence between species and simple species mixtures on dry matter production, in the third mowing, period 2023-2025

Variant	D.m. production	Difference		Signif.
	t/ha	t/ha	%	
a_1 - B.i. (100%) (ct.)	7,00	-	100	Control
a_2 - B.i. (75%) + O.v. (25%)	7,27	0,27	103,9	
a_3 - B.i. (50%) + O.v. (50%)	8,63	1,63	123,3	**
a_4 - B.i. (25%) + O.v. (75%)	9,70	2,70	138,6	***
a_5 - O.v. (100%)	8,87	1,87	126,7	**
	DL 5% =	1,10		
	DL 1% =	1,48		
	DL 0,1% =	1,96		

From the analysis of the results obtained in the third harvest, the highest production was achieved in the variant fertilized with N30P30K30, the difference recorded compared to the unfertilized variant was positive and significant (Table 6).

Table 6

The influence of fertilization on dry matter production, at scythe III, in the period 2023-2025

Variant	D.m. production	Difference		Signif.
	t/ha	t/ha	%	
b_1 - nefertilizat (ct.)	5,87	-	100	Control
b_2 - $N_{30}P_{30}K_{30}$	7,55	1,68	128,6	*
b_3 - $N_{50}P_{50}K_{50}$	7,07	1,20	120,5	
	DL 5% =	1,46		
	DL 1% =	2,43		
	DL 0,1% =	4,53		

CONCLUSIONS

The area where the research was conducted is very suitable for cultivating mixtures of perennial grasses and legumes for the establishment of temporary meadows.

Fertilization with nitrogen, phosphorus and potassium positively influenced the production of fodder. In the present study, fertilization with N30P30K30 was noted, obtaining the highest productions in the first and third mowings.

The mixture formed by *Bromus inermis* 25% + *Onobrychis viciifolia* 75% presented the best adaptability to the pedoclimatic conditions of the area.

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ASSESSMENT OF THE ECOLOGICAL IMPACT OF ADVANCED WEED CONTROL TECHNOLOGIES
/
EVALUAREA IMPACTULUI ECOLOGIC AL TEHNOLOGIILOR AVANSATE DE CONTROL AL BURUIENILOR

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Keywords: *ecological impact, weed control, pesticide use reduction, sustainable agriculture, biodiversity*

ABSTRACT

Weed control is a critical component of sustainable agricultural systems, directly influencing crop productivity, resource efficiency, and environmental health. In recent years, advanced technologies such as precision spraying systems, autonomous mechanical weeding devices, and biological control agents have emerged as viable alternatives to conventional herbicide-based practices. This paper evaluates the ecological impact of these advanced weed control technologies by analyzing their effects on soil quality, biodiversity, and non-target organisms. Comparative assessments between traditional and innovative methods are presented, focusing on the reduction of chemical inputs, greenhouse gas emissions, and soil compaction. The findings highlight both the benefits and potential risks associated with implementing high-tech weed management solutions and provide recommendations for integrating environmentally responsible practices into modern farming systems.

REZUMAT

Combaterea buruienilor reprezintă o componentă critică a sistemelor agricole durabile, influențând direct productivitatea culturilor, eficiența utilizării resurselor și sănătatea mediului. În ultimii ani, tehnologii avansate precum sistemele de pulverizare de precizie, echipamentele autonome pentru plivit mecanic și agenții biologici de control au apărut ca alternative viabile la practicile convenționale bazate pe erbicide. Această lucrare evaluează impactul ecologic al acestor tehnologii avansate de control al buruienilor prin analizarea efectelor asupra calității solului, biodiversității și organismelor netintă. Sunt prezentate comparații între metodele tradiționale și cele inovatoare, cu accent pe reducerea inputurilor chimice, a emisiilor de gaze cu efect de seră și a compactării solului. Rezultatele evidențiază atât beneficiile, cât și potențialele riscuri asociate implementării soluțiilor tehnologice moderne de gestionare a buruienilor și oferă recomandări pentru integrarea practicilor responsabile din punct de vedere ecologic în sistemele agricole contemporane.

INTRODUCTION

Weed management represents one of the major challenges in modern agriculture, significantly affecting crop productivity, resource efficiency, and environmental sustainability *(Jeyaseelan, A. et al., 2024).* Conventional weed control practices, particularly the extensive use of chemical herbicides, have contributed to increased agricultural yields over past decades; however, their long-term ecological consequences have raised growing concerns. Issues such as soil degradation, water contamination, biodiversity loss, and the development of herbicide-resistant weed species have highlighted the urgent need for more sustainable and environmentally responsible weed control solutions *(Narayanan, M. et al., 2024).*

In response to these challenges, advanced weed control technologies have emerged as promising alternatives to traditional approaches. These technologies include precision agriculture systems, sensor-based and vision-guided mechanical weeders, autonomous robotic platforms, targeted spraying systems, and non-chemical methods such as thermal, electrical, or laser-based weed suppression *(Cornish, C. M. et al., 2024)*. By enabling site-specific intervention and reducing the reliance on broad-spectrum chemical

applications, these innovations aim to minimize environmental disturbance while maintaining or improving weed control efficiency.

Assessing the ecological impact of such advanced weed control technologies is essential to ensure that their adoption contributes positively to agroecosystem health. Ecological impact assessment involves evaluating effects on soil properties, microbial activity, non-target plant species, beneficial insects, energy consumption, and greenhouse gas emissions. A comprehensive analysis of these factors provides valuable insight into the sustainability and environmental trade-offs associated with emerging weed management strategies *(Zhang, Y. et al., 2024).* Therefore, this study aims to assess the ecological impact of advanced weed control technologies by analyzing their influence on key environmental indicators and comparing them with conventional weed management practices. The findings are intended to support informed decision-making in agricultural technology development and policy, contributing to the transition toward more sustainable and resilient farming systems. *(Oyetunji, G. O. et al., 2024).*

Herbicides are among the most widely used agrochemicals for weed control because of their selectivity and cost effectiveness. By 2016, more than 2000 herbicide products representing approximately 15 distinct modes of action had been introduced globally *(Narayanan, M. et al., 2024).* These compounds are designed to suppress target weeds while minimizing crop injury, yet their performance is highly dependent on correct application. Phytotoxic effects can occur when herbicides are applied at rates exceeding recommendations, at inappropriate crop growth stages, or when spray volumes and equipment calibration are poorly managed. In practice, however, excessive or improper application is common. For example, the United Nations Office on Drugs and Crime reported that in coca production systems, herbicides and other agrochemicals are frequently applied at extremely high rates, resulting in severe risks to soils, surface waters, and surrounding biodiversity. Such examples illustrate how real-world management conditions can amplify ecological impacts well beyond intended weed targets *(Baćmaga, M. et al., 2024).*

Soils function as critical reservoirs for agrochemical contaminants and sustain diverse microbial communities, including bacteria, fungi, archaea, and protists. These organisms play central roles in organic matter decomposition, nutrient cycling, and the detoxification of xenobiotic compounds. Soil microorganisms also contribute directly to the degradation of herbicide residues, thereby influencing their environmental persistence and ecological footprint. At the same time, herbicide exposure can alter microbial community structure and function, producing effects that range from suppression of sensitive taxa to stimulation of specialized degraders. Long term herbicide use has been associated with declines in microbial biomass, enzyme activity, and functional diversity, ultimately impairing soil processes that support crop productivity and ecosystem stability *(Michael, I. et al., 2024).*

Recent evidence demonstrates that herbicide–microbiome interactions are strongly context dependent. Microbial responses vary according to herbicide chemistry, application rate, soil physicochemical properties, and broader environmental conditions. While some microbial groups are capable of metabolizing herbicides and using them as carbon or nutrient sources, others are inhibited or eliminated following exposure. These shifts can disrupt plant–microbe interactions in the rhizosphere, reduce nutrient uptake efficiency, and alter crop–weed competitive dynamics. Over time, such ecological changes may erode soil resilience and undermine agricultural sustainability. These risks are compounded by the rapid evolution of herbicide resistance. Continuous and intensive herbicide use has imposed strong selective pressure on weed populations, and by 2023 more than 500 documented resistance cases had been reported across 269 weed species involving over 160 herbicide modes of action. This trend reduces the long-term effectiveness of chemical weed control and often leads to further increases in herbicide use *(Oyetunji, G. O. et al., 2024).*

MATERIALS AND METHODS

CONVENTIONAL WEED CONTROL STRATEGIES

Chemical (Herbicide) Control

Herbicide application represents one of the most widely adopted approaches to weed management. Chemical control methods enhance production efficiency, support reduced-tillage farming systems, and generally require lower labor input and operational costs. Herbicides were initially developed to suppress weed species that compete with crops for essential resources such as nutrients, water, and light. They are also commonly used to control invasive plant species and eliminate undesirable vegetation in livestock production systems. A broad range of herbicides is currently available or under development for use in field crops. These products may be classified according to several criteria, including chemical family, application timing (pre-plant, pre-emergence, or post-emergence), mode of action, formulation, site of uptake, and

selectivity *(Das, T. K., et al., 2023).* Similar to other pesticide classes, herbicides contain biologically active compounds designed to penetrate plant tissues, cross cellular membranes, and interfere with vital physiological processes to achieve a toxic effect. To minimize adverse environmental consequences, herbicide use should be optimized and applied as efficiently as possible, thereby contributing to more sustainable agricultural systems. In this context, recent policy changes in Europe, such as Directive 2009/128/CE 2009, require farmers to significantly reduce herbicide use to protect human health and the environment. As a result, producers are increasingly encouraged to adopt integrated weed management strategies that combine several preventive and partially effective alternatives to chemical control.

Fig. 1 - Chemical weed management

Mechanical Control

Mechanical weed control is inherently complex and often requires the integration of multiple cultivation techniques to achieve economically viable results. This approach suppresses weeds by physically damaging or destroying plants, thereby reducing their competitive capacity. Mechanical methods can remain effective even when chemical or biological approaches are unsuitable and, in certain conditions, may outperform alternative weed control strategies. The selection of a mechanical control method depends on several practical factors, including crop type, soil characteristics, equipment costs, operating expenses, and labor availability. Mechanical weed management is closely linked to tillage practices, with cultivating tillage serving as the primary mechanism for weed suppression during crop growth. Cultivating tillage is typically performed after planting and involves shallow soil disturbance using tools such as tine harrows, rotary hoes, and row cultivators. These operations include whole-field, inter-row, and intra-row cultivation, which differ in their intensity and spatial focus relative to crop rows. Tillage offers several agronomic benefits, including enhanced soil aeration, improved moisture distribution, accelerated decomposition of organic matter, and increased accessibility of residues to soil microorganisms, while requiring relatively low labor input *(Paul, S. K., et al., 2024).*

Furthermore, reduced tillage systems can indirectly benefit the environment by decreasing pesticide and fertilizer runoff, thereby reducing water pollution risks. Mowing and cutting are additional mechanical techniques frequently used for weed management, particularly in turfgrass systems, roadsides, vineyards, orchards, pastures, and forage crops. Although these practices rarely provide complete weed control, they reduce leaf area, slow plant growth, and limit seed production. However, some weed species—especially perennial grasses—can adapt to repeated defoliation, making control more challenging. In such cases, frequent cutting is required to achieve effective suppression.

Fig. 2 - Mechanical weed management

NON-CONVENTIONAL WEED CONTROL STRATEGIES

Mulching

Mulching involves covering the soil surface with organic residues or synthetic materials to suppress weed emergence by inhibiting seed germination or obstructing seedling growth. In addition to weed control, mulching contributes to sustainable water management and biodiversity conservation, while also moderating

soil temperature and improving physical, chemical, and biological soil properties. Mulches may be organic—such as straw, sawdust, paper, weeds, or crop residues—or synthetic, primarily plastic-based materials. Plastic mulches, including black polyethylene films, are widely used for weed suppression in diverse agricultural systems, particularly in horticultural crops such as strawberry, tomato, eggplant, and melon species. Certain plastic mulches selectively block photosynthetically active radiation while allowing infrared radiation to pass through, increasing soil temperature and enhancing weed control efficacy. Mulching is generally more effective against annual weeds than perennial species (e.g., Cyperus spp., Elymus repens, Cynodon dactylon, Sorghum halepense), which can puncture plastic films and persist despite surface coverage.

Cover Crops and Living Mulches

The use of cover crops is widely recognized as a sustainable agricultural practice. Cover crops consist of living vegetation established before, after, or alongside a main crop and are typically terminated prior to planting the subsequent crop. Weed suppression occurs through competition for resources, occupation of ecological niches, and the presence of surface residues that inhibit weed emergence via physical, biological, and allelopathic mechanisms *(Jeyaseelan, A. et al., 2024).* Some cover crop species release allelochemicals from both living tissues and decomposing residues, which can inhibit weed seed germination. These species may be grown during fallow periods or concurrently with commercial crops. Beyond weed control, cover crops enhance soil structure, increase carbon sequestration, improve trafficability for machinery, and promote microbial and faunal biodiversity.

Fig. 3 - Weed management using cover crops

Fig. 4 - Weed management using mulch

Effective weed suppression with cover crops is strongly associated with high biomass production and rapid soil coverage. When biomass is insufficient or residues decompose rapidly, supplemental weed control measures—such as herbicide application—may still be required. The method used to terminate cover crops also influences weed suppression effectiveness. Mechanical termination techniques such as flail mowing and roller-crimping are commonly employed; flail mowing produces small residue fragments that decompose quickly, while roller-crimping creates a persistent mulch layer that provides longer-lasting ground cover. Living mulches are a specific type of cover crop that remains actively growing throughout the main crop's production cycle. Perennial living mulches may persist for multiple seasons without reseeding. These systems can reduce nutrient leaching, particularly nitrate losses, enhance carbon and nitrogen sequestration, control soil erosion, increase organic matter, and provide habitats for beneficial insects. Optimal performance requires fertile soils, adequate moisture, and low pressure from perennial weeds. Living mulches should be established only once the main crop is sufficiently developed to minimize competition for water and nutrients *(Das, T. K., et al., 2023).*

Soil Solarization

Soil solarization is an environmentally friendly and cost-effective soil disinfestation technique compatible with organic and integrated farming systems. This method relies on capturing solar energy by covering moist soil with transparent or black plastic sheets for a period of 4 to 12 weeks, thereby increasing soil temperature to levels lethal for weed seeds, pests, and pathogens. For optimal effectiveness, soil moisture must be maintained—often through drip irrigation—and consistent, intense solar radiation is required. Soil solarization is particularly suitable for Mediterranean and similar climates characterized by high summer temperatures and strong solar radiation *(Candido, V., et al., 2008*). Soil temperatures exceeding 40 °C can eliminate weed

seeds, insects, nematodes, and soil-borne fungal pathogens. While primarily used in greenhouse vegetable production systems, solarization has also proven effective in open-field conditions.

Thermal Weed Control

Thermal weed control employs high temperatures generated through flaming, hot water, steam, freezing, or fire to damage weed tissues without introducing chemical residues into soil or water. These techniques are selective, do not disturb the soil structure, and avoid bringing buried weed seeds to the surface, unlike mechanical cultivation. Flaming is the most widely used thermal method in both organic and conventional systems and typically involves propane burners or renewable fuel alternatives, such as hydrogen, producing combustion temperatures up to 1900 °C. Heat exposure rapidly disrupts plant cell membranes, causing cellular dysfunction and eventual plant death *(Bolat, A., et al., 2017).*

Young and broad-leaved weed species are generally more susceptible than mature or grass species. Flaming is most effective during early growth stages and against erect weeds, while its efficacy against grassy or prostrate species is limited. It is important to distinguish flaming from burning, as plant tissues are not ignited but rather heated sufficiently to rupture cell membranes. Thermal weed control can be enhanced when combined with tillage or mulching strategies; however, its widespread adoption is constrained by high fossil fuel consumption and sensitivity to factors such as exposure time, temperature, and energy input.

Weed Control through Livestock Grazing

Livestock grazing represents an underutilized yet increasingly effective approach to weed management. Integrating grazing into weed control programs has been recognized as a key strategy for addressing persistent weed issues. In agroforestry systems, combining livestock with trees and shrubs offers additional benefits, including improved biodiversity and enhanced soil fertility.

Targeted grazing aims to manipulate defoliation patterns to place weed species at a competitive disadvantage relative to desirable vegetation. The success of this approach depends on grazing timing, intensity, duration, and the livestock species used.

While grazing alone rarely eradicates established weed infestations, effective management requires controlled stocking rates and strategic fencing to regulate grazing pressure. Cattle, sheep, and goats are the most commonly used grazing animals for weed control. Among these, sheep are particularly effective due to their selective feeding behavior and adaptability. Grazing can replace chemical, mechanical, or mowing-based weed control in systems such as vineyards and orchards. Successful implementation requires careful management, including rotational grazing, temporary fencing, predator protection, and measures to prevent crop damage.

Fig. 5 - Soil solarisation

Fig. 6 - Weeding management using fire

Fig. 7 - Weed control through livestock grazing

RESULTS

Kaur, A. et al (2023) made a research of ecology, biology, and management of an agro-environmental weed ageratum conyzoides and they also discussed the environmental impacts. The author does not advocate a single weed control method, but rather promotes an integrated approach in which chemical control is limited, while mechanical, biological, and preventive methods are prioritized due to their reduced environmental impact.Ageratum conyzoides is a highly invasive weed that exerts significant ecological and economic impacts across multiple ecosystems, although empirical data quantifying the full extent of these impacts remain limited. In agricultural systems, the species affects a wide range of food and cash crops, forms persistent soil seed banks, and acts as a reservoir for numerous crop pests and viral pathogens, leading to substantial yield losses, particularly for smallholder farmers.

In forest ecosystems, its shade tolerance enables the establishment of dense understory populations that threaten native plant communities and alter forest structure. In grasslands and rangelands, the weed spreads rapidly, displacing native grasses and forbs, reducing pasture carrying capacity, and contributing to

fodder shortages and biodiversity loss. A. conyzoides also modifies soil properties by altering nutrient availability, soil chemistry, and microbial communities through root exudates and residue decomposition, thereby disrupting natural soil processes. Its aggressive colonization reduces habitat availability for native species, resulting in homogenized plant communities and declines in local biodiversity. Beyond ecological effects, the species poses risks to human health and livestock due to its toxic properties, causing allergic reactions and severe physiological disorders in humans and potentially lethal effects in grazing animals. Overall, the uncontrolled spread of A. conyzoides represents a serious ecological and economic threat, underscoring the urgent need for integrated, cost-effective, and environmentally sustainable management strategies *(Kaur, A. et al., 2023).*

Fig. 8 - Different growth stages of Ageratum conyzoides

Fig. 9 - The spread of Ageratum conyzoides in various habitats

Another study from Parven, A. et al (2024) analyzed the ecological impact of pre-emergence herbicides used in both agricultural and urban environments (such as green spaces, roadside areas, and residential zones), with a particular focus on herbicide dissipation in soil (their persistence and degradation behavior), their transport in the environment (including leaching into groundwater and surface runoff), and their effects on non-target organisms, especially soil microorganisms, non-crop vegetation, and aquatic organisms.The primary objective was to assess real ecological risks rather than solely agronomic efficiency.

The study employed a controlled laboratory-based experimental design to investigate the dissipation behavior, soil interactions, and ecological implications of selected pre-emergence herbicides in urban and agricultural soils. The methodological framework integrated physicochemical soil characterization, herbicide dissipation experiments, biological soil health assessment, and environmental and human health risk evaluation. Five distinct soils were selected to represent contrasting land-use systems: two urban soils collected from landscaped and residential environments and three agricultural soils collected from cultivated farmlands.

Soil samples were taken from the 0–20 cm topsoil layer, air-dried, homogenized, and sieved (<2 mm). Each soil was comprehensively characterized to determine its physicochemical properties, including texture (sand, silt, clay content), pH and electrical conductivity, total organic carbon (TOC), mineralogical composition, concentrations of iron (Fe) and aluminum (Al) oxides, functional groups of soil organic matter (via FTIR analysis). These parameters were selected due to their known influence on herbicide sorption, bioavailability, and degradation. Three widely used pre-emergence herbicides were investigated: Dimethenamid-P, Metazachlor, and Pyroxasulfone. These compounds were chosen because of their frequent application in both urban green spaces and agricultural systems, as well as their contrasting physicochemical properties and reported persistence in soil. Herbicide dissipation was assessed using soil incubation experiments under controlled conditions:

Soil samples (20 g each) were spiked with commercial herbicide formulations to achieve a concentration representative of field application rates. Samples were incubated at 21 ± 1 °C, in darkness, with moisture maintained at approximately 70% water-holding capacity. Control samples without herbicide addition were included. To distinguish biological degradation from purely chemical degradation, parallel samples were stored at −20 °C, inhibiting microbial activity. At predefined time intervals (0, 5, 10, 20, 30, 60, 90, 120, and 150 days), soil subsamples were collected and extracted using an acetonitrile–water solvent

system. Herbicide residues were quantified using liquid chromatography–mass spectrometry (LC–MS). Dissipation kinetics were modeled using first-order degradation equations, allowing calculation of degradation rate constants (k) and half-life values (DT_{50}).

To evaluate non-target biological effects, soil microbial activity was assessed through measurement of soil dehydrogenase activity (DHA), a widely accepted indicator of overall microbial metabolic activity. DHA was quantified spectrophotometrically and expressed as µg triphenylformazan (TPF) per gram of soil. This approach enabled assessment of whether herbicide residues adversely affected soil microbial functioning. Environmental mobility and contamination risk were evaluated using established indices: Groundwater Ubiquity Score (GUS) – to assess leaching potential, Leachability Index (LIX) – to evaluate soil-to-water transfer risk. Additionally, human non-carcinogenic risk was assessed by calculating: chronic daily intake (CDI), hazard quotient (HQ), hazard index (HI), considering exposure pathways such as incidental soil ingestion, dermal contact, and inhalation of contaminated particles. Risk calculations were based on standardized USEPA methodologies and assumed a conservative scenario corresponding to 50% herbicide dissipation.

The results demonstrated that all three herbicides followed first-order degradation kinetics across both urban and agricultural soils. However, dissipation rates varied significantly depending on soil properties. Degradation rate constants (k) ranged between 0.010 and 0.024 day^{-1} and corresponding half-life values (DT_{50}) ranged from 29 to 69 days.

Among the tested compounds, a clear hierarchy of persistence was observed: Pyroxasulfone > Metazachlor > Dimethenamid-P. Pyroxasulfone exhibited the longest persistence, indicating a higher potential for residual carryover and environmental transport. Contrary to concerns regarding toxicity to soil biota, the study found no significant inhibition of soil dehydrogenase activity following herbicide application. In several cases, soils with higher organic matter content exhibited increased DHA values, indicating that organic matter played a dominant role in sustaining microbial activity despite the presence of herbicide residues. This suggests that, under the tested conditions, the selected pre-emergence herbicides exerted minimal short-term adverse effects on soil microbial metabolism *(Parven, A. et al., 2024).*

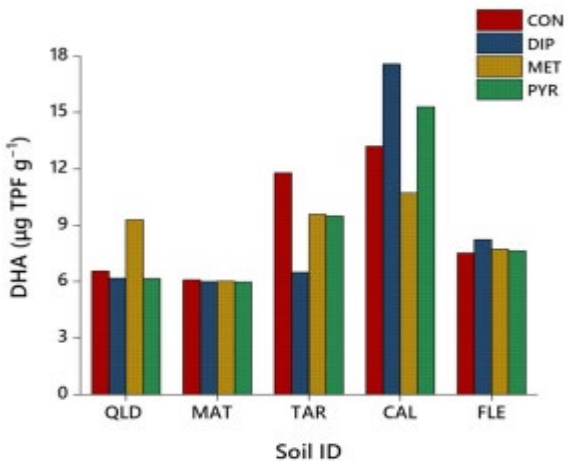

Fig. 10 - Soil dehydrogenase activity (DHA; µg TPF g^{-1} soil) in urban (CAL, FLE) and agricultural soils (QLD,MAT, TAR), untreated (CON) and treated with dimethenamid-P (DIP), metazachlor (MET) and pyroxasulfone (PYR)

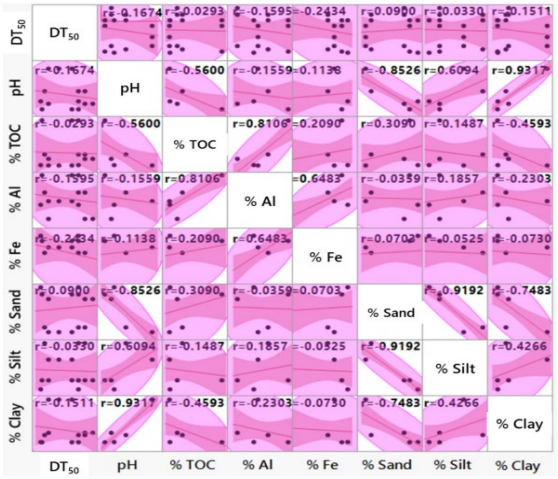

Fig. 11 - Relationship between soil physicochemical properties (predictor variables) and the half-life (DT_{50}) of dimethenamid-P, metazachlor and pyroxasulfone in urban (CAL, FLE) and agricultural soils (QLD, MAT, TAR)

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