ISAE 2025 - Proceedings

The 7th International Symposium on Agricultural Engineering - ISAE 2025

6th – 8th October 2025, Belgrade, Serbia

Belgrade 2025.

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Preface

Welcome to the 7th International Symposium on Agricultural Engineering, a gathering that reflects not only tradition but also the dynamic transformation of agriculture in the era of digital innovation. This Proceedings brings together contributions that embody the new direction of agricultural engineering—one that increasingly intertwines technology, sustainability, and knowledge-driven growth.

In recent years, agriculture has become a field where global challenges meet advanced solutions. Climate change, resource limitations, and the demand for sustainable food systems are now addressed through precision farming, automation, and data-driven decision-making. Digital technologies, from IoT-based monitoring and artificial intelligence to robotics and bioinformatics, are no longer the future—they are shaping the present of agricultural practices across the world.

This volume reflects that shift. Within these pages, you will encounter research that illustrates the integration of digital tools into every segment of agricultural production—from soil and water management, through plant and animal sciences, to post-harvest processing and the food industry. It is through these advances that we envision agriculture not only as a traditional practice but as a smart, interconnected, and resilient system prepared to face the decades ahead.

We extend our deep appreciation to the authors who have contributed their knowledge, creativity, and results. Your work strengthens the mission of this symposium: to serve as a hub where researchers, innovators, and professionals exchange ideas, form collaborations, and set directions for the agricultural engineering community.

As we open this 7th edition of ISAE, we do so with the conviction that digitalization and global innovation trends will continue to redefine our profession. We invite you to join us in dialogue, debate, and discovery as we collectively shape the sustainable, technology-driven agriculture of the future.

Thank you for being part of this important journey.

Asst. Prof. Dr. Aleksandra Dragičević
President of the Scientific Committee

Contents

Artificial Intelligence in Agriculture

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ISAE 2025 - Book of Abstracts
The 7th International Symposium on Agricultural Engineering

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STUDY OF SOIL–BASIN LISTER INTERACTION USING DISCRETE ELEMENT MODELLING APPROACH

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Abstract: This study focuses on the study of soil–tool interaction using the Discrete Element Modelling (DEM) approach for a basin lister equipped with a watercourse attachment. The aim was to understand and predict the behavior of soil under varying operating speeds (2 km/h, 3 km/h, and 5 km/h) using Altair EDEM 2025. The basin lister geometry was modeled using Creo Parametric 11 and imported into the EDEM environment, where sandy clay loam soil was represented using bonded spherical particles (3–5 mm radius). The contact interactions were simulated using the Hertz-Mindlin with bonding model. Key performance indicators such as height and width of cross bunds, ridges, watercourses, and draft force were recorded. Model validation was carried out using the angle of repose and inclined plane tests. The simulation trends showed strong agreement with experimental results, with relative error ranging from 11.11% to 28.16% across parameters. The study demonstrates the reliability of DEM as a virtual test bench for tool development and performance optimization in tillage systems.

Keywords: Discrete Element Method (DEM), basin lister, soil–tool interaction, EDEM Simulation, Watercourse formation, Draft force.

1. Introduction

Mechanization in agriculture plays a crucial role in improving efficiency, conserving natural resources, and boosting productivity, especially in semi-arid and rainfed areas. Implements like basin listers are highly effective in forming rectangular basins and directing water into controlled channels, thus enhancing in-situ moisture conservation, and reducing soil erosion [1]. Traditional methods of evaluating tillage implements rely on field experiments, which are time-consuming, expensive, and prone to variability due to soil and environmental factors. This has led researchers to adopt simulation-based methods, notably the Discrete Element Method (DEM), to study soil–tool interactions in a virtual and controlled setting [2]. DEM simulates soil as an assembly of individual particles interacting through defined contact laws. It has been successfully used to investigate forces, soil movement, and tool performance in various tillage operations such as moldboard ploughing, chiseling, and subsoiling [3,4]. However, limited studies have explored its application to basin listers with integrated watercourse attachments for rectangular basin formation. This study focuses exclusively on the DEM-based simulation of a basin lister using Altair EDEM 2025. The tool geometry was developed in Creo Parametric 11, and the soil was modeled using bonded spherical particles to replicate the behavior of soil. Simulations were performed under different operating speeds, and parameters like bund height and width, ridge formation, watercourse shape, and draft force were analyzed. The DEM model was validated using angle of repose and inclined plane tests, as suggested by Obermayr et al. [5], ensuring accurate replication of particle behavior.

2. Materials and Methods

2.1. Basin Lister

A tractor-mounted, basin lister with watercourse attachment was used for trials, as shown in Fig. 1. The implement is designed to form micro-basins across the field for in-situ water conservation, while the watercourse attachment facilitates surface drainage. As the implement is pulled by a tractor, the watercourse attachment (ridger) engages the soil first, creating a shallow furrow that functions as a surface drain. Following this, the lister unit operates periodically (controlled by the stop and release mechanism) to form cross bunds by lifting and throwing soil laterally across the furrow. This results in discrete basins aligned with the furrow, spaced at regular intervals.

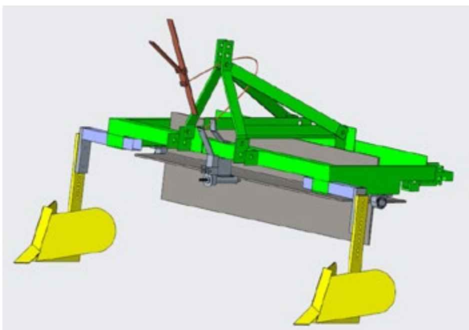


Figure 1 CAD Geometry of Basin Lister with watercourse attachment

Its main components include the main frame, lister unit, stop and release mechanism for lister unit, watercourse attachment (ridger) and hitch mast. The geometry was modeled in Creo Parametric 11 and exported into EDEM 2025.

2.2. Field conditions

The field soil was sandy clay loam, comprising 61.71% sand, 26.15% clay, and 12.14% silt. Soil samples were collected from 0–20 cm depth using the core cutter method, yielding an average moisture content (dry basis) of 13.84% and an average bulk density of 1490 kg/m³. Particle size distribution was assessed by passing air-dry soil through sieves ranging from 0.05 mm to 5 mm, with the highest particle distributions observed for 3 mm (19.28%) and 5 mm (12.01%) particles.

2.3. Discrete element modeling (DEM) simulations

The discrete element method (DEM) was employed to study soil-ridger interactions, with simulations run in Altair EDEM 2025. Computations were performed on a Dell Laptop with an Intel® Core i5 13th generation CPU @ 3170 GHz, Nvidia RTX 3050 6GB vRAM GPU and 16 GB of RAM.

2.3.1. Soil modeling

To ensure accurate and reliable simulation outcomes, constructing a representative soil particle model is crucial. In EDEM, particles are typically represented as spheres by default. However, using only spherical particles does not fully capture the complexity of real soil micro-aggregates. Prior research suggests that soil structures can be better modelled by grouping spherical particles into configurations such as lumps, columns, or nucleus-like assemblies as shown in Fig. 2. [7-9].

At present, there is no standardized guideline for determining soil particle sizes in discrete element simulations. Consequently, researchers typically select particle dimensions based on the number of particles required within the simulation domain and the limitations of available computational resources. A range of particle sizes has been employed in earlier soil-tool interaction studies, with a preference for spherical particles. For example, Ucgul et al. [10-12] utilized spherical particles with radii ranging from 5 mm to 10 mm in their analyses.

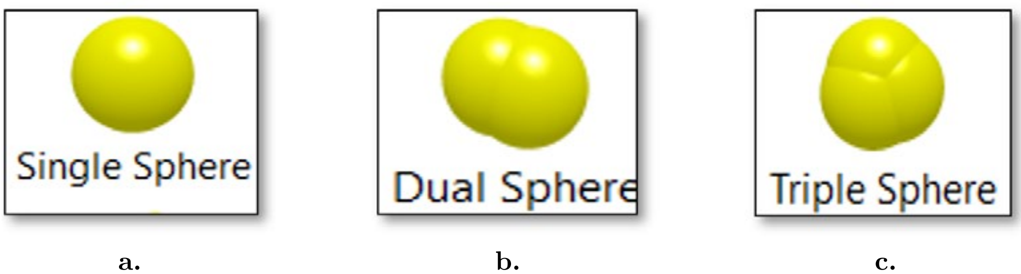


Figure 2 Soil particles shapes for soil bin development in EDEM a) Lump, b) Column, c) Nuclei

In this study, spherical particles with radii of 3 mm and 5 mm were used to model soil. These sizes were chosen considering the simulation domain's geometry and the performance constraints of the computing system. A combination of particle shapes and sizes was incorporated to represent the heterogeneity of soil structure more realistically. The proportions of the various soil particles used in the simulation are summarized in **Table 1.**

Table 1 Proportion of soil particles used in the simulation

Soil particle	Proportion %	No. of particles
3 mm single sphere	70.21	3266476
5 mm single sphere	19.84	923482
5 mm double sphere	7.63	355062
5 mm triple sphere	2.3	107339

2.3.2. Model parameters

The accuracy of a Discrete Element Method (DEM) simulation significantly depends on the selection of an appropriate contact model and the precise definition of DEM parameters. The contact model governs how particles behave upon interaction, while the base model describes the mechanics of particle-to-particle and particle-to-geometry collisions. According to Li et al. [13], cohesive interactions—such as liquid bridge bonding and inter-particle cohesion—play a critical role in influencing tillage resistance and the degree of soil disturbance. In alignment with their findings, the Hertz-Mindlin contact model with bonding was used in this study to replicate the cohesive nature of agricultural soils.

The parameters used in the DEM simulations are summarized in Table 2 and categorized into two groups: material parameters and contact parameters.

Material parameters include:

- Soil particle density,
- Poisson's ratio, and
- Shear modulus, for both the soil and the tool material (mild steel). Soil density was determined experimentally, while other values—such as the mechanical properties of mild steel and theoretical values for soil Poisson's ratio and shear modulus—were obtained from existing literature (Deng et al., 2016). The shear modulus (G) of mild steel was computed using the following relation:

$$G = E / 2(1+ \upsilon) \qquad (1)$$

where,
G is the shear modulus (Pa);
E is the elastic modulus (Pa); and
υ is Poisson's ratio.

Contact parameters include the coefficient of restitution, the coefficient of static friction, and the coefficient of rolling friction for soil particles and soil-tool interactions.

The static friction coefficients were determined experimentally through angle of repose and inclined plane tests, while the coefficient of restitution and rolling friction coefficients were obtained from literature [14]. Additional calibration support for these values was drawn from Fang et al. [15], who conducted systematic testing of soil frictional behaviour.

Table 2 DEM input parameters

Parameters	Value
Radius of the filling element, r (mm)	3 and 5
Soil particle density, ρ1 (kg/m3)	1490
Poisson's ratio of the soil particles, υ1	0.4
Shear modulus of the soil particles, G1 (Pa)	1×106
Poisson's ratio of Mild steel, υ2	0.30
Shear modulus of Mild steel, G2 (Pa)	1×1010
Density of Mild steel, ρ2 (kg/m3)	7800
Coefficient of restitution between soil and soil, e1	0.6
Coefficient of rolling friction between soil and soil, e2	0.2
Coefficient of static friction between soil and soil, e3	0.57
Coefficient of restitution between soil and Mild steel, f¬1	0.3
Coefficient of rolling friction between soil and Mild steel, f¬2	0.05
Coefficient of static friction between soil and Mild steel, f¬3	0.5
Percentage of the Rayleigh Time Step %	20
Simulation time, t (s)	5

In EDEM, the time step controls how frequently interaction calculations are performed during the simulation. This step size is typically defined as a percentage of the Rayleigh time step, which represents the time it takes for a shear wave to propagate through a particle. Based on software recommendations, this study used a time step equivalent to 20% of the Rayleigh time step.

The Rayleigh time step (Tr) was computed using the following equation:

$$Tr = \frac{\pi R \sqrt{\frac{\rho}{G}}}{0.1631\ \upsilon + 0.8766} \tag{2}$$

where,
R is the particle radius,
ρ is the particle density,
υ is the Poisson's ratio and
G is the particle shear modulus.

2.3.3. Model validation

The angle of repose (AOR) is a key parameter representing the steepest angle at which a mass of soil remains stable without sliding, measured with respect to the horizontal plane. It is typically calculated using the height and diameter of a soil heap formed naturally on a flat surface.

Among several established methods to determine AOR, the lifting cylinder technique is widely accepted for its simplicity and accuracy [16]. In this study, a vertical funnel with an upper diameter of 265 mm, a lower opening of 50 mm, and a height of 350 mm was used. The funnel was filled with soil to a height of 325 mm and lifted vertically at a constant speed of 0.05 m/s. This allowed the soil to form a conical pile on a flat platform. The test was repeated three times to obtain an average AOR value for sandy clay loam soil at a moisture content of 13.84% (dry basis).

To validate the soil model used in the simulation, the same test setup was replicated in Altair EDEM. The simulated particles were allowed to form a similar heap under gravitational influence to determine the soil's repose angle digitally.

The angle of repose was found to be 30° in both the physical and virtual experiments, indicating that the simulated soil behaviour closely matched real-world conditions. This validation supports the reliability of the DEM particle configuration used in this study. The visual comparison of both test results is illustrated in **Fig. 3.**

a. **b.**

Figure 3 Angle of repose test a) Laboratory test for field soil and b) Test in EDEM software for prepared soil

2.3.4. Soil-basin lister modeling

A three-dimensional (3D) CAD model of the basin lister equipped with a watercourse attachment was developed using Creo Parametric 11, maintaining a 1:1 scale to ensure geometric accuracy. This model was then imported into Altair EDEM 2025, where a virtual soil bin was constructed with dimensions of 3000 mm in width, 2000 mm in length, and 400 mm in height, as illustrated in Fig. 4. These dimensions were selected to facilitate the analysis of soil behaviour under varying tillage depths and forward speeds.

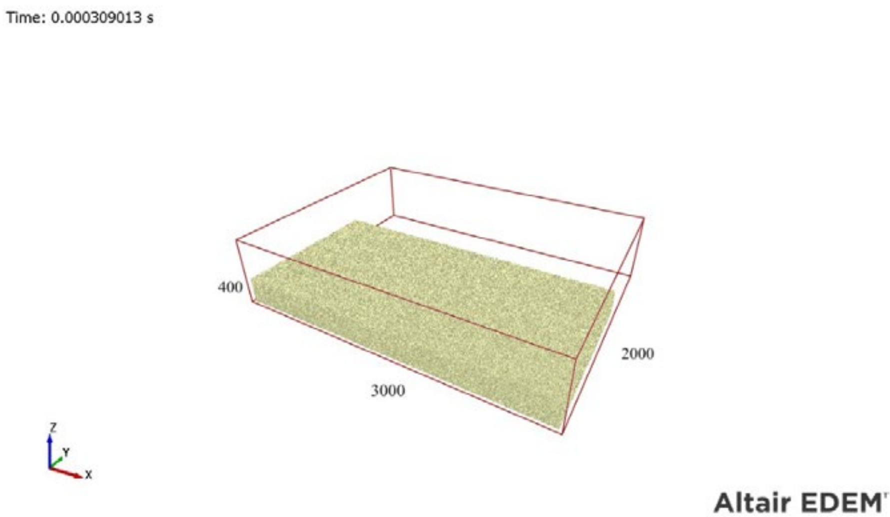


Figure 4 Soil bin in EDEM Software

During the simulation, key performance parameters such as draft force and soil disturbance characteristics—including cross bund height, cross bund width, side ridge height, side ridge width, watercourse depth, and watercourse width—were monitored using the same measurement methodology as employed in the physical experiments.

To evaluate the accuracy of the DEM simulations, relative error (RE) between the simulated outputs and the experimentally measured values was calculated using the following equation, adapted from Chen et al. (2013):

$$\text{RE}\ (\%) = \frac{M - S}{M} \times 100 \tag{3}$$

where,
RE is relative error (%)
M is measured value
S is simulation value

3. Results and Discussion

3.1 Cross bund height

Fig. 5 shows the variation in cross bund height with respect to operational speed (2 km/h, 3 km/h, and 5 km/h). Cross bund height is defined as the vertical distance between the top of the cross bund and the basin level. It is influenced by the speed of operation of the implement.

It is observed that cross bund height increases with increasing speed. At higher speeds, the lister blade interacts with the soil more aggressively, resulting in greater lifting of soil particles and their deposition at higher altitudes. There is also an increase in the kinetic energy imparted to the soil particles. The excess laterally scattered soil particles generated by the watercourse attachment (ridger) are subsequently carried by the lister blade, resulting in greater soil volume displacement.

The maximum cross bund height of 161 mm is achieved at a forward speed of 5 km/h, while the minimum height of 136 mm is recorded at 2 km/h. The available experimental data also reveal the same trend—an increase in bund height with increasing forward speed. These results highlight the tool's efficiency at high speeds for bund development but also caution that excessive soil scattering could occur in field scenarios without boundary control.

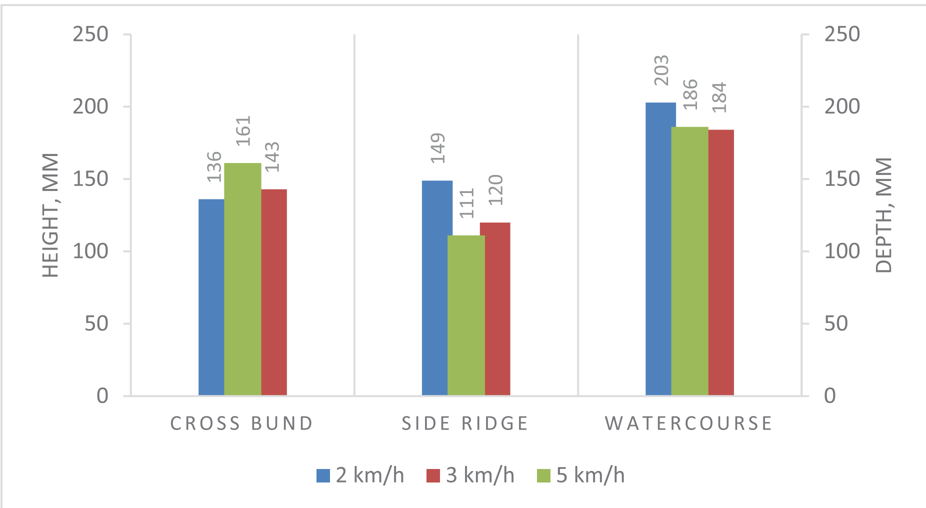


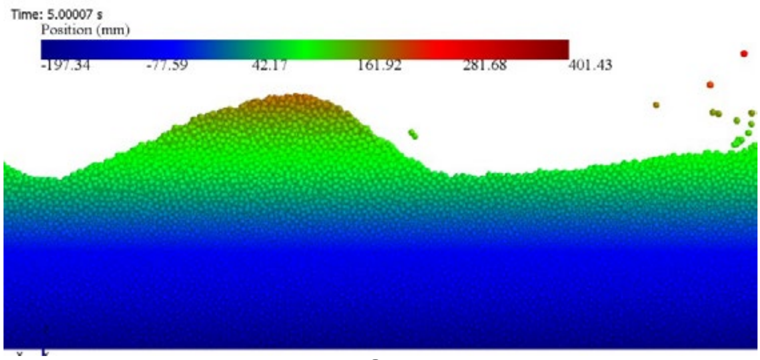
Figure 5 Effect of operating speed on height/depth

3.2. Cross bund width

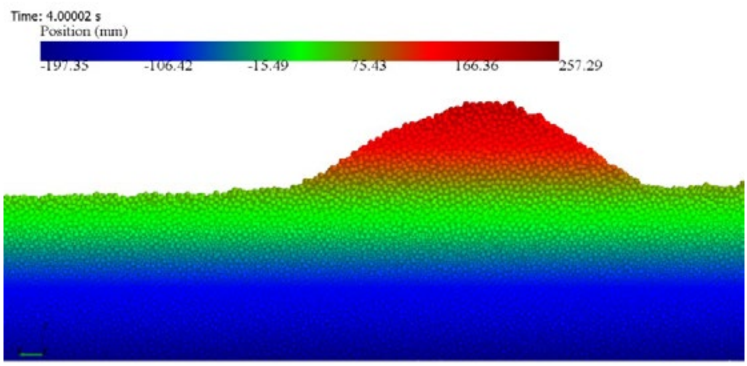
Fig. 6 shows the variation in cross bund width with respect to operational speed (2 km/h, 3 km/h, and 5 km/h). Cross bund width is defined as the horizontal distance between the lowest points of the bund on both sides.

It is observed that cross bund width remains relatively unchanged or increases slightly at very high operating speeds. The experimental data available for the study also exhibit a similar trend, showing a slight increase in cross bund width as operating speed increases. These results indicate that an optimum operating speed must be considered to achieve the desired bund profile without excessive soil dispersion.

Figure 6 Effect of operating speed on width



a.



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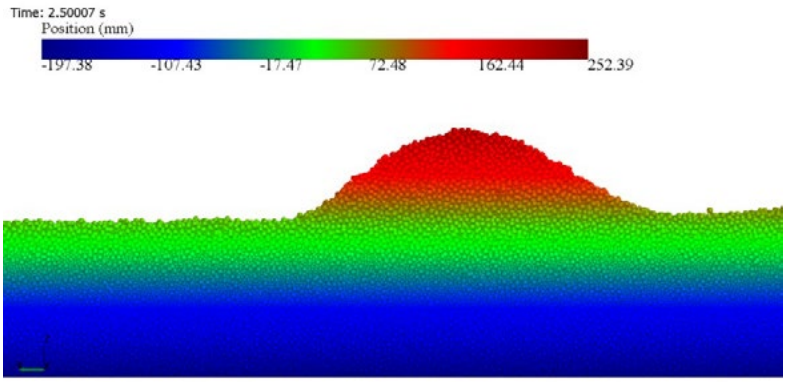

c.

Figure 8 Cross bund profile at a) 2 kmph, b) 3 kmph, c) 5 kmph speed of operation for DEM simulation

3.3. Side ridge height

Fig. 5 shows the variation in side ridge height with respect to operational speed (2 km/h, 3 km/h, and 5 km/h). Ridge height is defined as the vertical distance between the top of the side ridge and the basin level.

It is observed that ridge height decreases with an increase in operating speed. This decreasing trend is attributed to the greater velocity imparted to the soil particles at higher speeds. As the particles are displaced laterally, the increased velocity results in more widespread scattering of soil, preventing the formation of tall ridges.

A maximum ridge height of 149 mm is achieved at 2 km/h, while a minimum of 111 mm is observed at 5 km/h. A similar trend is observed in the experimental data.

3.4. Side ridge width

Fig. 6 shows the variation in side ridge width with respect to operational speed (2 km/h, 3 km/h, and 5 km/h). Ridge width is defined as the horizontal distance between the two ends of the ridge at the basin level.

It is observed that ridge width increases with increasing operational speed, reaching a peak at 3 km/h, and then begins to decrease at higher speeds. This decrease is caused by irregular soil throw patterns at high speeds, which narrow the ridge slightly. Another notable observation is that the excess laterally scattered soil particles are carried forward by the lister plate, resulting in minimal change in ridge width even at higher speeds.

The maximum ridge width of 289 mm is achieved at 3 km/h, while the minimum of 265 mm is recorded at 2 km/h. An increasing trend in ridge width is also observed in the experimental data.

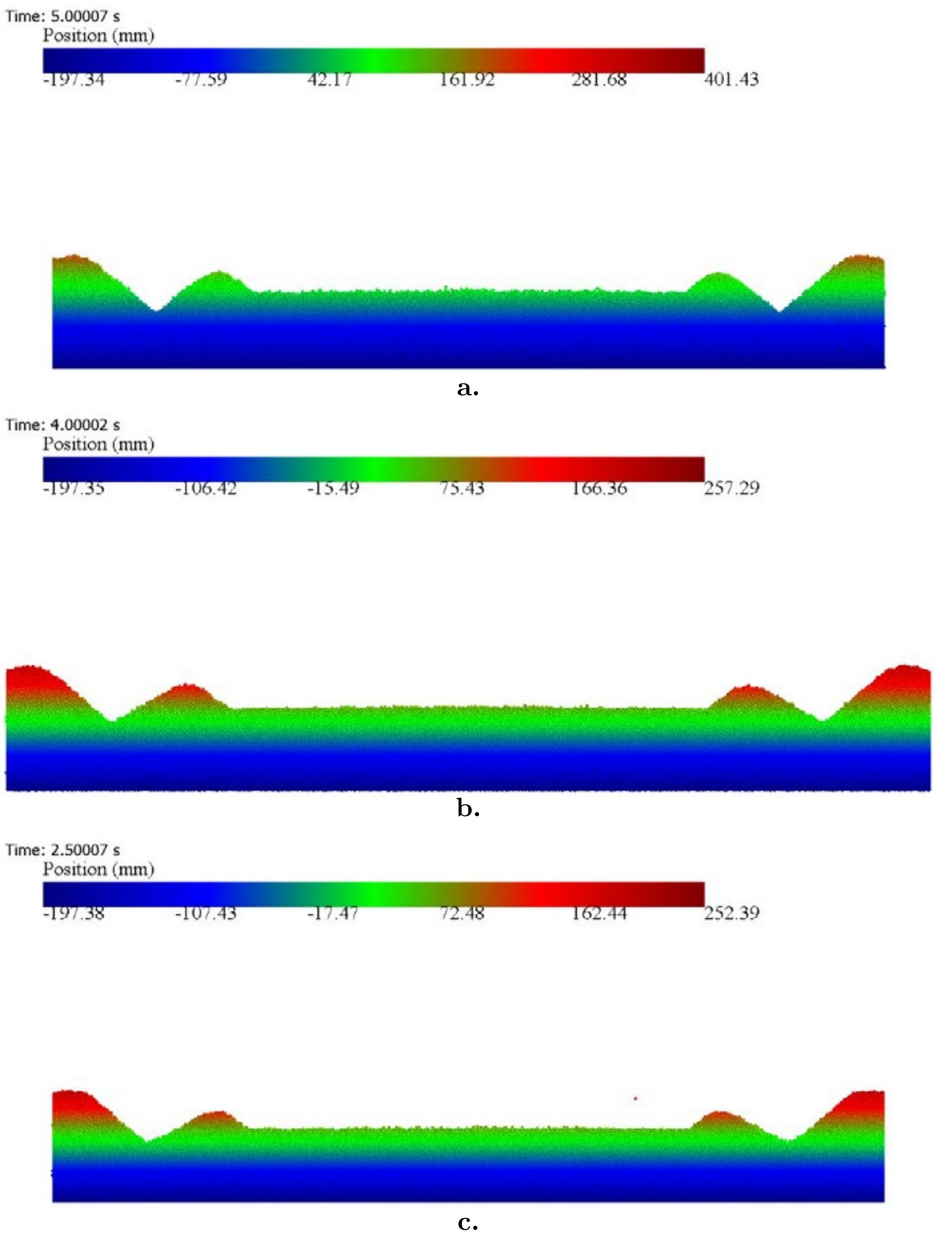

Figure 9 Side Ridge and Watercourse profile at a) 2 kmph, b) 3 kmph, c) 5 kmph speed of operation for DEM simulation

3.5. Watercourse depth

Fig. 5 shows the variation in watercourse depth with respect to operational speed (2 km/h, 3 km/h, and 5 km/h). Watercourse depth is defined as the vertical distance between the bottom-most point of the watercourse and the top of the ridge formed alongside it.

It is observed that watercourse depth decreases with increasing speed and remains relatively constant at higher speeds. This reduction is attributed to insufficient tool penetration time at higher speeds. At slower speeds, the implement has more time to penetrate and carve the soil downward, creating a deeper watercourse. In contrast, faster speeds compromise the time available for effective cutting action, leading to shallower and less defined channels.

The maximum watercourse depth of 230 mm is recorded at 2 km/h, and the minimum of 184 mm at 3 km/h. A similar decreasing trend is observed in the experimental data.

3.6. Watercourse width

Fig. 6 shows the variation in watercourse width with respect to operational speed (2 km/h, 3 km/h, and 5 km/h). Watercourse width is defined as the horizontal distance between the top-most points of the watercourse.

It is observed that watercourse width increases with the increase in operating speed. The broader width at higher speeds is due to increased soil momentum, which spreads the particles more widely across the field surface. Although higher speeds enable broader coverage, they also lead to flatter and shallower watercourses, which may reduce water retention efficiency.

The maximum watercourse width of 540 mm is recorded at 5 km/h, and the minimum of 510 mm at 2 km/h. A similar trend is observed in the experimental data.

3.7. Draft

Fig. 7 shows the variation in draft force with respect to operational speed (2 km/h, 3 km/h, and 5 km/h). Although the draft force has generally increased with speed, this increase has not followed a strictly linear pattern. From 2 km/h to 3 km/h, the draft force has shown a substantial rise, increasing from 430.27 kgf to 561.38 kgf. However, the further increase to 588.57 kgf at 5 km/h has been comparatively marginal.

This non-linear behaviour is attributed to several interrelated mechanical and simulation-based factors. The first factor is increased soil scattering: at higher speeds, soil is thrown more laterally due to increased kinetic energy. This lateral movement has prevented the accumulation of soil directly in front of the implement. Without a dense resistance front, the tool has encountered lower passive pressure, reducing the draft load despite the increase in speed.

The second factor is reduced tool–soil contact time at high speeds. As speed increases, the contact duration between the lister blade and soil particles decreases, limiting the time available for penetration and engagement. Consequently, less soil is displaced per unit of contact, and the resistance force tends to plateau instead of rising proportionally with speed.

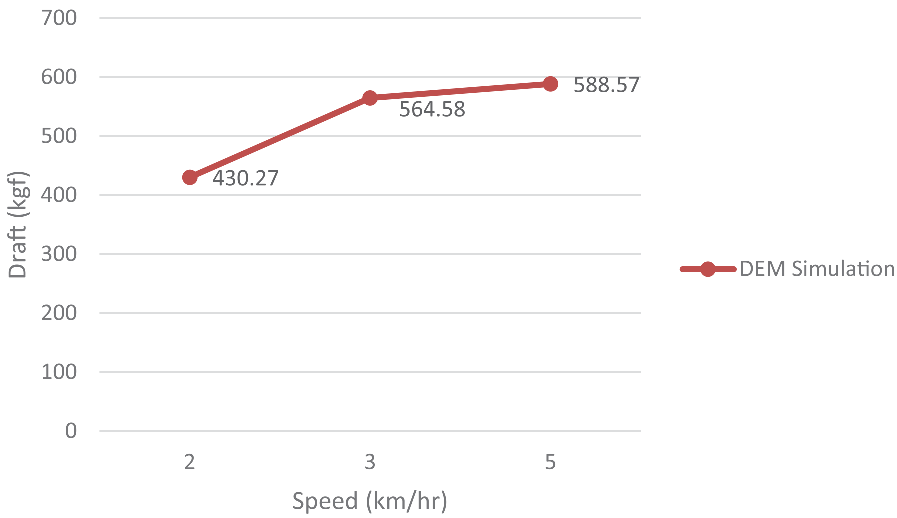

Figure 7 Effect of operating speed on draft

The third factor is the limitations of the DEM model to replicate the real-life soil conditions, resulting in the unexpected change in the trend.

A similar trend has been confirmed through experimental studies.

3.8. Relative Error

The relative error between the experimental values and the DEM-simulated results was calculated for various parameters at different operating speeds (2 km/h and 3 km/h). The relative error provides a quantitative assessment of the accuracy and validity of the DEM model by comparing it against field-tested values. Tab. 4 presents the relative error between the experimental data and DEM simulation results.

Tab. 4 Relative error between Experimental and DEM simulation study

SN	Speed km h^{-1}	Error, %						
		Height of Cross Bund	Width of Cross Bund	Height of Side Ridge	Width of Side Ridge	Depth of Wa-ter-course	Width of Wa-ter-course	Draft
1	2	11.11	17.31	24.16	19.69	12.5	17.87	28.16
2	3	14.88	24.93	16.50	18.13	13.61	19.78	12.05

The relative error for cross bund height ranged from 11.11% at 2 km/h to 14.88% at 3 km/h, while the error for cross bund width increased from 17.31% to 24.93%. For side ridge height, the relative error decreased from 24.16% at 2 km/h to 16.50% at 3 km/h.

Similarly, side ridge width showed a small variation in error, reducing from 19.69% to 18.13%.

In terms of watercourse dimensions, the relative error for depth increased slightly from 12.50% to 13.61%, while the width error rose from 17.87% to 19.78% as speed increased. The relative error for draft force showed the highest variation, decreasing from 28.16% at 2 km/h to 12.05% at 3 km/h.

4. Conclusions

The research on the Discrete Element Modelling (DEM) of soil–basin lister interactions has provided meaningful insights into the effects of operating speed on performance parameters such as cross bund height and width, side ridge formation, watercourse profile, and draft force. The following conclusions are drawn from this study:

- The cross bund height has shown an increasing trend with speed, ranging from 136 mm at 2 km/h to 161 mm at 5 km/h, due to enhanced soil uplift and lateral soil movement carried by the lister blade.
- The cross bund width has remained relatively stable but has shown a slight increase at higher speeds. It ranged from 651 mm at 2 km/h to 620 mm at 5 km/h, indicating that bund width is less sensitive to speed variations compared to height.
- The side ridge height decreased consistently with increased speed. The maximum ridge height of 149 mm was recorded at 2 km/h, reducing to 111 mm at 5 km/h, due to reduced soil deposition and increased lateral scattering at higher kinetic energy levels.
- The side ridge width increased up to 289 mm at 3 km/h but dropped slightly to 270 mm at 5 km/h, suggesting an optimum range of operating speed for maximum ridge width without over-scattering of soil.
- The watercourse depth decreased with increasing speed, from 230 mm at 2 km/h to 184 mm at 3 km/h, and remained nearly constant thereafter, reflecting a reduction in penetration effectiveness at higher forward velocities.
- The watercourse width increased with speed, ranging from 510 mm at 2 km/h to 540 mm at 5 km/h, showing that higher speeds cause greater lateral displacement of soil in the watercourse region.
- The draft force increased non-linearly, with values ranging from 430.27 kgf at 2 km/h to 588.57 kgf at 5 km/h. The increase from 3 km/h to 5 km/h was comparatively smaller, attributed to reduced soil-tool engagement and soil deflection behaviour in the DEM environment.
- The maximum relative error between experimental and DEM simulated values for the observed parameters was found to be 14.88% for cross bund height, 24.93% for cross bund width, 24.16% for side ridge height, 19.69% for side ridge width, 13.61% for watercourse depth, 19.78% for watercourse width, and 28.16% for draft force. These values confirm the reliability of the DEM model within acceptable simulation accuracy limits.

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FORECASTING OF THE TRACTORS FUEL CONSUMPTION WITH MACHINE LEARNING METHODS BASED ON REMOTE MONITORING DATA

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Abstract. For sustainable development of agriculture, still necessary to reduce per-hectare costs of technological operations in the crop production. One of the important components per-hectare costs is diesel consumption of tractors. In addition to saving fuel, it is necessary to increase the productivity of machine and tractor units, which in turn often depends on the properties of the processed environments. In this case, such medium is soil, which can differ both in its granulometric composition and in physical properties. Therefore, it is necessary to use operational control of the equipment and take some measures to regulate these aspects. Today, this is becoming possible thanks to the development of modern digital technologies, gradually being introduced into our daily lives. One of that solutions is ability to machines and equipment remote control at field work performing. These systems include sensors that have opportunity to control various technical and technological processes. Data received from the sensors accumulated in the navigation controllers memory, devices that allow to determine geolocation and next transmit all data to remote server. Then the information about machine and tractor units operations can be analyzed and used for identify various relationships, and most importantly, for operation management of technological processes in the on-line mode. One of the options for applied application of monitoring data is response functions of modeled processes prediction with artificial intelligence algorithms. In this paper, was forecasted the tractor diesel consumption at field operations performing. As a result of existing machine learning algorithms review for regression analysis, was selected the most preferred. As parameters, was selected the output indicators of the machine-tractor unit operation and the properties of the processed medium. During preprocessing, was used the median filter for smoothing outliers. The forecast model was selected with the results of a comparative analysis from the following: random forest, prophet, skforecast, lstm architecture. For each of the listed options, was selected hyperparameters in order to increase the accuracy of the final forecast. After analyzing the results of the constructed models, was determined algorithms which demonstrate the greatest predictive accuracy and results stability. The obtained results can be used for field works planning in order to improving the efficiency of crop production technologies.

Keywords: fuel consumption, soil moisture, remote monitoring, artificial intelligence, machine learning.

1. Introduction

For sustainable development of agriculture, still necessary to reduce per-hectare costs of technological operations in the crop production. One of the important components per-hectare costs is diesel consumption of tractors.

Reducing energy costs during field work by reducing fuel consumption of tractors is a fairly urgent task. This is important from both the economic and environmental points of view [1].

In addition to saving fuel, it is necessary to increase the productivity of machine and tractor units, which in turn often depends on the properties of the processed environments.

In this case, such medium is soil, which can differ both in its granulometric composition and in physical properties [2,3,4].

Therefore, it is necessary to use operational control of the equipment and take some measures to regulate these aspects. Today, this is becoming possible thanks to the development of modern digital technologies, gradually being introduced into our daily lives.

One of that solutions is ability to machines and equipment remote control at field work performing [5].

These systems include sensors that have opportunity to control various technical and technological processes. Data received from the sensors accumulated in the navigation controllers memory, devices that allow to determine geolocation and next transmit all data to remote server. Then the information about machine and tractor units operations can be analyzed and used for identify various relationships, and most importantly, for operation management of technological processes in the on-line mode.

One of the options for applied application of monitoring data is response functions of modeled processes prediction with artificial intelligence algorithms [6].

Therefore, the aim of this study is to determine the most preferred methods for predicting fuel consumption of tractors.

2. Materials and methods

The fuel consumption of the tractor engine was taken as the response function. Based on previous studies, it was found that this indicator can be used as an indicator of the energy component of field work. Instantaneous fuel consumption has a high correlation with the traction resistance of machine-tractor units (MTU) [7, 8].

Instantaneous fuel consumption was determined by the electronic control unit of the engine (ECU). Then the obtained data were read and transmitted to the server, and then processed. An experiment to determine fuel consumption was carried out in the Bagansky district of the Novosibirsk region, on the basis of the farming enterprise Joint-stock company Ivanovskoye. Early spring moisture closure was carried out on fields with the southern chernozem soil type. Harrowing was carried out after autumn deep cultivation. The MTU included a Kirovets K-742M tractor and a tooth harrow UPA-BZ-26-2 with a working width of 26 meters (see Fig. 1). The soil cultivation depth was 4 cm.

Figure 1. Machine-tractor unit for harrowing

The variable factors were the operating speed of the unit, the pressure in the tractor tires and the soil moisture. The speed varied in the range of 8-12 km/h, with a sampling step of 2 km/h. The speed was measured by the on-board system of the tractor and controlled using the on-board navigation controller AutoGRAPH-GSM/SL. The speed was adjusted by the operator from the tractor cabin. The tire pressure changed in the range of 1.6-2.0 bar with a step of 0.2 bar and was determined by a classic pressure gauge. Soil moisture in the field varied in the range of 23.7-48.6% and was determined using the XMSJ RS485 Soil moisture sensor. The length of the run was 360 m, the acceleration strips between the main 100-meter sections were 20 meters. As the unit moved along the 100-meter section, changing values of instantaneous fuel consumption were recorded. Then, the data accumulated in the controller were transmitted to the server.

During the processing of experimental data, a comparative analysis of the results of regression models obtained on the basis of machine learning tools when calculating the dependencies of instantaneous fuel consumption with the parameters and operating modes of the machine-tractor unit, soil moisture was carried out.

All sets include the operating speed of the unit, tire pressure, soil moisture, and the forecast of instantaneous fuel consumption is estimated by the mean absolute error. For a fragment of the time series, the mean absolute error was calculated in 20% of measurements.

Data sets:
- General – includes all 209 measurements;
- Speed 8 km/h – only measurements at a speed of 8 km/h;
- Speed 10 km/h – only measurements at a speed of 10 km/h;
- Speed 12 km/h – only measurements at a speed of 12 km/h;
- Pressure 1.6 bar – only measurements for tire pressure of 1.6 bar;
- Pressure 1.8 bar – only measurements for tire pressure of 1.8 bar;
- Pressure 2.0 bar – only measurements for tire pressure of 2 bar.

For the random forest algorithm, all combinations were used, since the time sequence is not explicitly required. For prophet, skforecast, LSTM, this compliance was used, so the models were built for data sets divided by pressure value, and also, for the experiment, for the entire original set. The hyperparameters of the algorithms are given in Table 1.

Table 1. Hyperparameters of algorithms

№	Algorithm	Hyperparameters
1	Random forest	Number of trees, division criterion, maximum depth, minimum number of division samples, minimum number of leaf samples
2	Prophet	Trend function type, trend flexibility, number of inflection points
3	Skforecast	Number of lags, parameters of the external regressor, size of the sliding window
4	LSTM	Sequence length, activation function, loss function, number of epochs, batch size

3. Results and discussion

Results for the Random Forest algorithm:
- Overall: 1.6369739338361882;
- Speed 8 km/h: 1.9637122268254719;
- Speed 10 km/h: 1.165333207625737;
- Speed 12 km/h: 3.6301107773096812;
- Pressure 1.6 bar: 0.0508220056246067;
- Pressure 1.8 bar: 3.011780696858281;
- Pressure 2.0 bar: 0.04739439109912847.

The mean absolute error (MAE) for predicting fuel consumption using the random forest regressor varies significantly across the data subsets. 2 bar and 1.6 bar exhibit the lowest MAE values (approximately 0.047 and 0.051, respectively), indicating that the model is more effective at predicting fuel consumption for these subsets. 1.6 bar exhibits the highest MAE value (approximately 3.01), indicating that the model is less effective on this particular data subset and suggests an analysis in terms of potential errors in this set. The MAE values for the different speed subsets range from 1.1 to 3.63, which is on average higher than the MAE for the entire dataset of approximately 1.63 and suggests that the individual models generated for different speeds and pressures will be the most accurate.

Results for Prophet algorithm:
- Overall: 8.272455192343283;
- Speed 8 km/h: 7.969207186855739;
- Speed 10 km/h: 8.309359924139137;
- Speed 12 km/h: 3.367734521967469;
- Pressure 1.6 bar: 3.7172202265657432;
- Pressure 1.8 bar: 31.13053194805851;
- Pressure 2.0 bar: 0.595311008648995.

The lowest MAE (0.5953) was for the 2.0 bar pressure dataset, indicating the best forecasting performance among the four datasets using the default Prophet model. The highest MAE (31.1305) was for the 1.8 bar pressure dataset, indicating the worst forecasting performance and, as with the random forest, indicating possible errors in this set of measurements.

Results for Skforecast library algorithm:
- Overall: 11.023009523809534;
- Speed 8 km/h: 2.3266933333333517;
- Speed 10 km/h: 9.567466666666615;
- Speed 12 km/h: 14.620890909090974;
- Pressure 1.6 bar: 15.375579999999998;
- Pressure 1.8 bar: 2.7777066666666097;
- Pressure 2.0 bar: 0.49036363636360425.

The Skforecast ForecasterAutoreg model with the RandomForestRegressor regressor and a time lag of 5 units was trained on the training data for each data frame. This variant showed the worst average values compared to the previous one.

Results for LSTM architecture:
- Overall: 3.7808886122703553;
- Speed km/h 8: 4.037993240356446;
- Speed 10 km/h: 4.469339497884112;
- Speed 12 km/h: 0.661593475341796;
- Pressure 1.6 bar: 2.540041147867837;
- Pressure 1.8 bar: 9.91820897420247;
- Pressure 2.0 bar: 5.145878295898438.

The lowest error value for the general dataset and, overall, the most stable results among algorithms focused on time series forecasting confirm the generalization capabilities of neural networks. Experimenting with different LSTM architectures, hyperparameters (e.g., number of layers, units, epochs, batch size, sequence length) or including additional relevant features can potentially improve the forecast accuracy and reduce the mean error (MAE).

4. Conclusion

Taking into account the obtained values of the forecast error, as well as the requirements for hardware resources, the Random Forest algorithm is the most preferable. It is also possible that on longer measurement sequences, other algorithm options will show more accurate results. As a prospect for further research, it can be said that taking into account a larger number of factors influencing the formation of fuel consumption will allow for more accurate forecasting.

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MOTIVATION FACTORS IN VIDEO GAMES FOR PREDICTING LIFE SATISFACTION IN A PRE-ADOLESCENT RURAL POPULATION

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Abstract. The aim of this cross-sectional online study was to test the role of motivation factors for playing online video games in predicting the relative contribution of variance in the construct of life satisfaction in preadolescents. The Pertinent sample included (N = 423) children in rural areas of the Republic of Serbia (M age = 10.56, SD = 1.10). The following original measuring instruments were applied: Motivation For Massive Multiplayer Online Role-Playing Game Questionnaire (MMORPG), Satisfaction with Life Scale (SWLS),and Video game genre. The reliability coefficients of the analyzed variables are satisfactory (≥ 0.70). Exploratory factor analysis extracted 10 factors interpreted as: progression, game mechanics, competition, communication, relationship, teamwork, discovery, role-playing, character editing, and escaping reality. The extracted latent dimensions suggest that the 10-factor structure of motivation for playing online video games is differentiated, with certain factors being more relevant than others for interpreting motivation for playing. The multiple regression analysis explained 25% of the variance of the criterion variable of life satisfaction. In the prediction of the dependent variable of life satisfaction based on a model of 10 motivation factors – the factors advancement ($\beta = -0.52$, $p \leq 0.01$) and escaping reality ($\beta = -0.48$, $p \leq 0.01$) showed statistical significance. This suggests that they have a significant function in predicting the perception of life satisfaction among students living in rural areas. The results obtained expand knowledge about the relevance of the relationship between motivation factors and life satisfaction in the pre-adolescent rural population.

Keywords: motivation, video game genre, online gaming, pre-adolescents, rural

Introduction

At the start of the 20th century, children and pre-adolescents spent their free time playing in nature. Yet, with the development of modern electronic technologies and the creation of an environment in which there are fewer and fewer children's playgrounds for leisure activities, they moved to a virtual environment, where online video games with the help of audiovisual technology are becoming the most used entertainment medium, where the concept implies a background story that, according to certain rules, relates to the plot of a fictional, non-productive and voluntary entertainment video game, character or event (Utomo, 2025). As electronic devices have become more accessible to the wider public, virtual games – whether played on a computer, game console, or mobile phone – have become more accessible, with around 3.5 billion people in the world's population playing them in 2023 (Nash & Brady, 2022). The aforementioned authors list various categories of video games: action, action-adventure, adventure, role-playing games, simulations, strategy games, sports games, puzzle games, and idle games. In the virtual stage domain, i.e. in the temporary social community formed by the players, discourses of different virtual roles are encountered, which are both retold and contribute to the construction and transformation of the entered identities, as the players maintain the accepted diversities from the virtual world even when they stop playing digitally, and in this way become characters shaped by the narrative (Yi et al., 2025).

The authors have established a negative correlation between gaming and pro-social behavior and empathy, risky determinants of video game addiction, and negative consequences of MMORPG (Massive Multiplayer Online RolePlaying Game) games in those who play for a large number of hours every day (Razum & Glavak-Tkalić, 2025). Research findings (Cabellos et al., 2021) indicate that males, singles, younger players, and those with obsessive-compulsive disorders, depression, and lower levels of anxiety manifest a tendency toward addictive video game playing. Preadolescents with video game addiction symptoms showed a lower level of satisfaction with real life than adolescents without such symptoms, i.e. they were more satisfied with their virtual life compared to their objective life, with the consequences being reversed for those who were not addicted to gaming (Rahimi et al. 2023). On the other hand, the results of the study (Razum and Huić, 2023) draw attention to the fact that problematic gaming is manifested in children who play video games, where the negative implications were perceived by a minimal proportion of those who recovered after such unpleasant experiences. Players of MMORPG games are generally not addicted to video games, they claim (Vandewalle et al., 2022). Those who attend parties in bars or clubs choose games instead of socializing, so they are more likely to socialize online instead of in person. Also, researchers (Jun et al., 2025) believe that moderate use of digital technology by preadolescents is not negatively correlated with mental health. An empirical study (Rutledge et al., 2025) found a low intensity but significant positive interaction between enjoyment of digital content and personal well-being.

The relationship between playing video games and mental health is complex. The obtained differential results are probably a consequence of the motivation for playing games being in close analogy with the individual well-being of the player, where intrinsically motivated playing has positive, while extrinsically motivated playing has negative implications on the level of individual well-being (Razum et al., 2025). However, the authors (Gao et al., 2025) found that the satisfaction of basic psychological needs through playing video games is partially interdependent with subjective well-being. Other researchers have found that characteristic motivation patterns are correlated with Internet video games. Such networking with other players presupposes co-dependence in the virtual domain. The original motivation model (Yee, 2006) was oriented exclusively to video games of the MMORPG genre. The original motivation model (Yee, 2006) was oriented exclusively to video games of the MMORPG genre. It hypothesized 10 lower-order factors: progression, game mechanics, competition, socialization, relationships, teamwork, discovery, role-playing, character editing, and escaping reality, which are condensed into three basic factors: achievement, socialization, and immersion (Kahila et al., 2025). Researchers (Haltigan et al., 2023) identified three components: achieving game results, socialization through pleasant communication with other players, and coping with reality through different video game genres.

The aim of this research is to examine the relevant factors of motivation for playing online video games in the prediction of the variance of life satisfaction – a component of the perceived subjective well-being of players in pre-adolescence. In accordance with the results of previous research and the aim of this study, designed as a cross-sectional study, two alternative hypotheses were tested: It is expected to define a ten-dimensional model of the construct of motivation factors in pre-adolescents (H1) and it is expected that motivation factors for playing video games are statistically significant in predicting the level of life satisfaction in online video game players, with the motivating factors of advancement, competition and escaping reality being negatively correlated with the criterion of life satisfaction, and the factors of game mechanics, communication, relationships, teamwork, discovery, role-playing and character editing being positively correlated with the perception of life satisfaction in elementary school students (H2).

Method

Based on a brief overview of empirical studies, it is noted that entertaining video games are correlated with both negative and positive consequences of life satisfaction, i.e. psychological well-being, and that additional empirical studies to test their relationships are still lacking.

Participants and procedure

The pertinent online sample (N = 423) consisted of preadolescents living in rural areas. The average age of participants across the entire territory of the Republic of Serbia was 10.56 ± 1.10 years. The link to the survey measuring instruments was distributed via e-mail addresses available from personal contacts and social networks. After giving informed consent, participants were asked to forward the invitation to participate with the instruments designed in a digital version to other people via electronic technology using the platform (Google Forms). The online completed battery of measuring instruments could not be correlated with the identity of the participants, because instead of their names and e-mail addresses, the participants entered their passwords using all available characters. At the beginning of the research, the participants were given brief explanations in electronic form on how to respond, and they could quit at any time without any consequences. The survey lasted approximately 20 minutes. The research was conducted in September 2025, and was approved by the Ethics Committee of the Serbian Academy of Innovation Sciences in Belgrade.

Motivation Questionnaire for Playing Massive Multiplayer Online Games (MMORPG)

The MMORPG (Williams et al., 2008) includes 21 items that measure the preference of motives for playing online video games. Since this measuring instrument is used for the first time in the Serbian population, it was back-translated from English to Serbian and adapted to represent the original content. Participants were asked to answer each question using a five-point Likert-type scale, with a higher score indicating a greater salience of certain motives. The overall internal reliability of the scale, i.e. Cronbach's alpha, is $\alpha = 0.80$.

Satisfaction with Life Scale (SWLS)

The Satisfaction with Life Scale (Pavot & Diener, 1993) contains five items that assess the level of satisfaction with life. An example of a statement: "My life is very close to what I consider ideal." Participants responded on a seven-point scale (1= strongly disagree to 7= strongly agree). The final score is the sum of the ratings on individual statements, where a higher value indicates greater satisfaction with life. The internal reliability of the Cronbach's α coefficient is ($\alpha = 0.79$).

Video game genre

The participants were given 11 distributions of online video games, where they had to choose for each one whether they play it or not. The genres of these games were taken from well-known websites for computer and information technology (Bug. hr1). In order to more fully describe the different forms of games and to make it easier to evaluate which type of game they play most often, the most popular video game genres were added: "shooters" (First Person Shooter, FPS), action games, strategy games, role-playing games (RPG), massive multiplayer online games (MMO), adventure, platform, simulation and sports games. In addition, the following genres were added: Multiplayer Online Battle Arena (MOBA) and Survival games. For each selected genre, respondents are asked to write the name of a video game of that genre that they play. For each selected genre, participants were asked to write the name of a video game of that genre that they played. This was used to control how participants categorized video games. Subsequently, all participants were tested for classifying a particular video game into the selected genre. If participants disagreed, the game was added to the genre that the majority of other players had chosen for the same game. Given the relatively large number of participants who listed a fun video game that fit the MMORPG genre, these 12 categories were also formed during data processing. In addition, participants were offered the option Other in which players were asked to list an example of a specific game.

Video game playing time

During the survey, participants were asked to estimate the average number of hours they spent playing online video games over a seven-day period.

Statistical data processing methods

Before conducting multivariate analysis, the normality of the distributions of all manifest variables was checked. The reliability of the results was determined by Chrombach's α coefficient of internal coexistence. The normality of the distribution of variables was tested by the coefficient of skewness and kurtosis. The statistical procedures of descriptive statistics, exploratory factor analysis (EFA) and multiple linear regression analysis were used. Conclusions were drawn at the level of statistical error ($p \leq 0.05$, $p \leq 0.05$). The data were analyzed in the computer program SPSS, version 26, using the IBM statistical software package.

Results

Descriptive data

Table 1 calculates the frequencies and percentages in the sense of "out of a hundred" of participants who play a particular genre of online video game.

Table 1. Frequencies and percentages of participants in games of certain genres of video games

Video game genre	Frequency	%
"First person shooter" (FPS)	82	19.38
Role-playing games (RPG)	71	16.78
Massive multiplayer online game (MMO)	59	13.94
Strategy games	60	14.18
Multiplayer Online Battle Arena (MOBA)	54	12.76
MMOROG	25	5.91
Action games	19	4.49
Sports games	20	4.72
Adventures	12	3.08
Survival games	9	2.83
Simulations	6	1.32
Platform	4	0.94
Other	2	0.47

Inspection of the table cells reveals that participants frequently play video games of different genres online: the mean value of the genres they enjoy is 3.95 (SD = 2.14). They

play on average 17.88 hours per week (SD = 14.03).
Using the multivariate statistical method of confirmatory factor analysis, the principal components method and the given Promax factor rotation on the online video game motivation questionnaire and life satisfaction scale in Table 2, the following factors were extracted: progression (F_1), game mechanics (F_2), competition (F_3), communication (F_4), relationship (F_5), teamwork (F_6), discovery (F_7), role-playing (F_8), character editing (F_9), escaping reality, (F_{10}), and life satisfaction (F_{11}). An identical configuration of the latent structures of online video game motivation and life satisfaction has also been defined in research (Johannes et al., 2021; Razum & Huić, 2023).
Testing the structural model revealed the following indices: $\chi 2/df$ (130, N = 487) = 218.56, p ≤ .000; CFI = .964; TLI = .915; RMSEA = .039, 90% CI [.026, .052]; SRMR = .035, which shows a satisfactory fit to the data (Jovičić & Mitrović-Dragutinović, 2018).

Table 2. Scope of rotated Promax main components and utilities

Factor	Item	Standard factor saturation	h2
Progression	Fastest character level up	0.60	0.40
	Obtaining rare items that most players will never have	0.78	0.82
	Becoming powerful	0.67	0.38
Game mechanics	Optimizing the character for the role	0.80	0.53
	Using a character builder or template to plan character development from the lowest level	0.29	0.75
	Knowing as much as possible about the mechanics and rules of the game	0.50	0.68
Competition	Competing against other players	0.78	0.39
Communication	Meeting other players	0.60	0.47
	Chating with other players	0.90	0.52
Relationship	Having important conversations with other players	0.77	0.78
	Share your personal problems with your online friends	0.62	0.65
Teamwork	Playing in a group	0.66	0.82
	Enjoing working with others in a group	0.76	0.43

Discovery	Enjoying exploring the world for the sake of exploring	0.75	0.64
	Enjoying searching for computer-controlled characters or a location that most people don't know about	0.70	0.56
Role-playing	Making up stories and personal histories for your characters	0.73	0.37
	Playing the role of your character	0.64	0.45
Character editing	Matching character's clothing/armor in color and style	0.70	0.83
	Character appearance different from other characters' appearance	0.83	0.59
Escaping reality	Escaping the real world	0.76	0.77
	Playing to avoid thinking about your real-life problems and worries	0.75	0.61
Life satisfaction	My life is very close to what I consider ideal.	0.77	0.40
	My living conditions are extraordinary.	0.60	0.54
	I am satisfied with my life.	0.90	0.36
	I have achieved important things in my life so far.	0.71	0.78
	If I were to live my life over again, I wouldn't change almost anything.	0.59	0.62

Annotation. h2 = Communality (sum of squared factor loadings or percentage of variance on the extracted factor); All factor loadings are statistically significant ($p \leq 0.01$).

The basic descriptive statistical parameters of motivation for playing online video games and life satisfaction are shown in Table 3.

Table 3. Basic descriptive parameters of the examined items

Items	M	SD	Sk	Ku
Progression Fastest character level up	3.25	1.60	0.17	0.92
Obtaining rare items that most players will never have	3.28	1.17	0.92	0.10

Becoming powerful	3.66	1.01	0.25	0.87
Game mechanics Optimizing the character for the role	4.01	0.87	0.84	0.20
Using a character builder or template to plan character development from the lowest level	3.33	1.16	0.36	0.77
Knowing as much as possible about the mechanics and rules of the game	3.57	3.53	0.77	0.34
Competition Competing against other players	3.50	1.08	0.45	0.65
Communication Meeting other players	3,38	1.10	0.59	0.36
Chating with other players	1.22	1.05	0.62	0.59
Relationship Having important conversations with other players	2.83	0.88	0.10	0.05
Share your personal problems with your online friends	2.24	1.20	0.93	0.93
Teamwork Playing in a group	3.57	1.22	0.84	0.12
Enjoing working with others in a group	3.90			0.86
Discovery Enjoying exploring the world for the sake of exploring	3.86	0.86	0.36	0.32
Enjoying searching for computer-controlled characters or a location that most people don’t know about	3.74	1.12	0.52	0.43

Role-playing Making up stories and personal histories for your characters	1.85	1.03	0.44	0.67
Playing the role of your character	2.18	1.24	0.67	0.70
Character editing Matching character's clothing/armor in color and style	2.15	1.29		
Character appearance different from other characters' appearance	2.90	1.30	0.15	0.45
Escaping reality Escaping the real world	2.72	1.38	0.28	0.15
Playing to avoid thinking about your real-life problems and worries	2.93	1.25	0.35	0.66
Life satisfaction My life is very close to what I consider ideal.	3.82	1.66	0.49	0.78
My living conditions are extraordinary.	4.58	1.70	0.80	0.90
I am satisfied with my life.	4.84	1.72	0.12	0.84
I have achieved important things in my life so far.	4.53	1.80	0.23	0.56
If I were to live my life over again, I wouldn't change almost anything.	3.60	1.87	0.36	0.42

Legend. M - arithmetic mean; *SD* - standard deviation; *Sk* = skewness; *Ku* = kustosis; The value of the standard error *(SE)* of indicator *Sk* is 0.13, and of *Ku* is 0.22.

Based on empirically calculated arithmetic means, it is observed that participants have the maximum average for the item (Life satisfaction M = 4.84), and the minimum for the item (Chatting with other players M = 1.22), while the maximum variability of results was achieved for the item (Knowing as much as possible about the mechanics and rules of the game SD = 3.53), and the minimum for the item (Becoming powerful SD = 1.03). The obtained coefficients of skewness and kurtosis are not outside the standard range of ±2, which is a prerequisite for conducting subsequent statistical multivariate analyses (Kline, 2023).

In order to examine the contribution of predictors of motivation factors for playing video games in explaining the variance of the criterion variable of life satisfaction in pre-adolescence, multiple linear regression analysis was applied (Table 4).

Table 4. Prediction of life satisfaction factors based on motivation factors

Predictors	**β**	**SE**
Progression	-0.52**	0.05
Game mechanics	0.15*	0.02
Competition	0.30 **	0.03
Communication	0.38**	0.09
Relationship	0.19*	0.06
Teamwork	0.16*	0.08
Discovery	0.28**	0.03
Role-playing	0.14*	0.04
Character editing	-0.48**	0.01
Escaping reality	0.62	
R	0.28	
R^2	0.25	

Legend. *β* = Standardized regression partial coefficient Beta; *R* = coefficient of multiple correlation, R^2 = coefficient of multiple determination; *SE* = The standard error of estimate of the regression parameter *β*; ** $p \leq 0.01$.* $p \leq 0.05$.

By inspecting the cells of the regression matrix, it is observed that the analyzed factors of motivation for playing video games explained a total of 25% of the average square deviation from the arithmetic mean – the variance of the life satisfaction criterion. The extracted factors progression (β = -0.52, p ≤ 0.01) and escaping reality (β = -0.48, p ≤ 0.01) had the highest statistically significant values of standardized regression coefficients. This suggests that players who had a more prominent motivational factor (progression) during the fun game, as well as those who perceived the factor (escaping reality) more intensely, manifested lower levels of satisfaction with their lives. However, multiple regression analysis, despite a significant probability level, did not explain 75% of the variability in life satisfaction. Therefore, it is recommended for future research with a longitudinal design to examine some other predictor variables in the preadolescent population.

Discussion

Given that the motivation to play and life satisfaction are increasingly researched in the world, the aim of this cross-sectional study was to test the role of the motivation factor for playing video games in predicting the variability of the dependent variable life satisfaction in online video game players. The pertinent online sample included (N = 423) participants from rural areas of the Republic of Serbia, with an age range of 10 to 11 years.

Studies of online video game players are mainly based on male participants (Amal, et al., 2025; Pan et al., 2025). It is possible that female video game players participate less in psychological research because, compared to men, they are perceived to be "serious" gamers to a lesser extent, and instead of perceiving gaming as a daily hobby of great importance, they perceive it as a second-rate activity. However, in the United States, an approximate number of male and female gamers has been observed (Saffari et al., 2025), where female gamers are recognized as "core gamers" in whom video games are an important part of life, in which they invest a lot of free time, and who enjoy playing with others.

The preadolescents tested in this study played for an average of 2 hours and 30 minutes each day, which is consistent with previous research (Iskandar & Kamila, 2024; Liu et al., 2025). It is possible that some players spend more time playing because they are more intensely motivated by goals that require longer-term play to achieve, and future empirical studies may further test this hypothesis. Realistically, more time is probably needed to realize goals that are interdependent with the factor of advancement or the achievement of power than with socialization with other players, since in online video games interaction with other players is usually present from the beginning of the video game. Since different motives have differential cohesion with subjective well-being, it is likely that examining them as time-directed and as psychological health status could predict different results. This is especially important because the general conclusion formed by the health public that longer gaming is correlated with undesirable implications such as video game addiction, so it is important to correct these attitudes if they are not exact, they emphasize (Jun et al., 2025).

Exploratory factor analysis – using the principal components method on the Motivation Questionnaire for Playing Massive Multiplayer Online Games, 10 factors were extracted, interpreted as: progression, game mechanics, competition, communication, relationship, teamwork, discovery, role-playing, character editing, and escaping reality. The multiple regression analysis explained 25% of the variance in life satisfaction among online video game players. In the prediction of the criterion variable of life satisfaction based on the 10-factor model of motivation structure – the factors progression and escaping reality showed statistical significance. A lower level of perceived life satisfaction was demonstrated by players who play to bring their character to a high level and achieve power, along with collecting original items and pieces of equipment, as well as players who play to escape reality. The obtained factor results suggest that the latent factor structure of motivation for playing online video games is differentiated, with some latent dimensions being more relevant for interpreting motivation for playing than others.

In this study, the following motivation factors for playing video games were extracted from pre-adolescent gamers: progression, game mechanics, competition, communication, relationship, teamwork, discovery, role-playing, character editing, and escaping reality, which are consistent with the factor structure (Williams et al., 2008). The tested model suggests a good fit to the data (overfitting), which implies flexibility in the application of these 10 motivation factors outside the genre of multiplayer online games. Also, in accordance with the results of the study (Fuster et al., 2012), it was found that players are encouraged by various motivation factors, which are generally interpreted as the realization of goals in the game (progression, game mechanics and competition), correlation with other players (communication, relationship, teamwork), exploration of the virtual world and its content (discovery, role-playing and character editing), and especially the escaping reality is emphasized. However, a smaller number of isolated motivational factors influence the subjective well-being of online video game players. The factors progression and escaping reality significantly negatively predict the level of life satisfaction construct. Players who are more motivated by the factor of progression during the game, as well as those who are more intensely motivated to play by escaping the realities of life, manifested a lower level of the dependent variable – life satisfaction. The motivation factor for advancement includes the elements of quickly leveling up a character and acquiring rare items so that an imaginary character in clothing or armor becomes powerful. Character level in video games is a weaker indicator of efficiency since in most entertainment games, players, with effort and time, achieve the maximum character level. However, rare items or pieces of equipment rarely manifest in an online video game, suggesting that the player has invested a lot of time and effort, so they are a kind of status symbol and indicator of achievement. Therefore, power in video games is correlated with the possession of a significant amount of resources or, most often, strength in combat. Being powerful presupposes that what other individuals cannot do. At the same time, power is realized through time, effort, and the development of gaming skills, which draws attention to the fact that the player has experience and is effective in that video game. In other words, players who are dissatisfied with their lives are expected to look for ways to compensate for their perceived failure. Perhaps they therefore dedicate themselves to gaming in order to manifest their abilities in a virtual environment and to have their success identified. In this context, it is important to additionally report why acquiring rare items and achieving power showed a slightly higher degree of saturation with the progression factor compared to quickly raising the character's level.

The relevance of the motivating factor of escaping reality in predicting life satisfaction is not unexpected. It is assumed that individuals who are less satisfied with life will try to distance themselves from the factor of escaping reality. They achieve this through immersion in unreal worlds and the perception of potential characters, especially if they complement in video games what they assume to be their limitations in reality. These findings are consistent with the authors' (Kalınkara & Talan, 2025) statement that children with symptoms of addictive gaming are less satisfied with their lives than those who are not addicted to playing virtual games. Additionally, addicted gamers are less satisfied with their real lives than with those in virtual life, while the opposite is true for non-addicted gamers. Since escape from reality has been identified as a relevant factor, it is concluded that video games generally provide a distraction from everyday life, especially if the player is dissatisfied with their everyday life.

The remaining eight extracted motivation factors in this study are not statistically significant in predicting players' life satisfaction, probably because they are in significant interaction with the factors of progression and escaping reality. For example, the factor of game mechanics is strongly interconnected with the factor of advancement. For example, the game mechanics factor is closely interconnected with the progression factor. Perhaps knowledge of the rules of the game is essential for efficiency in achieving goals in a video game, so the game mechanics factor does not directly explain the player's life satisfaction, but rather does so through the progression factor. At the same time, it is possible that because the model was applied to players of games of different genres, and not only to players of the original MMORPG genre (Yee, 2007), some isolated factors do not have statistical relevance. For example: discovery, role-playingand character editing, which are characteristic of the genres of online video games RPG, MMO and MMORPG, since the elements of these games allow for creative imagination of the story and appearance of the character. However, the separate factors of communication, relationships and team are not emphasized because these latent socialization dimensions are satisfied by players in reality. Given that players use games of different genres, it is likely that their motivation for social life has a wider range than staying in potential worlds such as the MMORPG genre for players (Amal et al., 2025).

Previous empirical studies on the positive and negative implications of playing video games have given inconsistent findings. Differences in gaming time between dependent and independent gamers and correlations between gaming time and other problematic behaviors, such as aggression, have been identified in research (Khalid et al., 2025). On the other hand, the authors (Jun et al., 2025) did not identify a correlation between playing video games and subjective well-being. The discrepancy in negative consequences identified in previous studies is likely explained by the differentiation between mental health status or psychological well-being. Mental health status is defined by two correlated components: positive mental health, i.e. subjective well-being and life satisfaction, and mental disorders, i.e. the manifestation or non-manifestation of mental disorders (Fahrudin et al., 2024). Previous research on the interdependence of mental health problems and video game addiction has not sufficiently focused on the positive mental health of gamers. The results of this research suggest that certain motivation factors interact more intensely with life satisfaction than other factors, so it is possible that introducing factors of motivation for gaming would allow for a more complete examination of the relationship between playing fun video games and mental health status. For example, it can be expected that online video games due to motivational factors, such as escaping reality, have moderating effects between playing time and negative implications, and that playing due to motivational factors (socialization) is a moderator between playing time and positive consequences of playing.

Also, in studies of motivation for playing video games, age has been minimally examined as a possible determinant of certain motivational factors. Future studies should test whether players differ in the genre of video games they choose based on their age, with the assumption that adult players are more motivated by relaxation than pre-adolescents and less motivated by motivational factors (competition or advancement). The explanation for such a hypothesis is their need for efficiency, which they satisfy in real life at their daily workplace or family life, while they use video games for relaxation after work and other obligations.

Different video game genres differ in terms of the player's goals and the forms of communication with the player's environment. Therefore, genre choice can be positively and negatively correlated with different motives for playing. Given that video games emphasize different elements, the following dilemmas arise: 1) do players who play for achievement prefer genres in which their success is realistically scored, e.g., shooters, and 2) do players with a more salient motivation factor, e.g., character customization, tend to prefer video games in which they can optimize the appearance and behavior of their character in color and style, as they can in games of the role-playing genre. Additionally, playing video games with multiple genres simultaneously complicates the findings of studies that test a single genre or specific video game, and explain their findings only in that discourse. It is assumed that such players also play other games, so the fact that the researcher approached the participants through a particular game should not be used to strictly classify players according to genre or to generalize about players and the distribution of specific forms of game. If certain motivational factors generate the use of games of differentiated genres, it is likely that players play games of multiple characteristic game forms at the same time in order to respond to all their motives. Therefore, it is interesting to examine differences in motivational patterns in players who prefer only one genre of online video games compared to those who play multiple genres simultaneously, with the possible moderating effect of motives for playing video games.

Conclusion

In this cross-sectional study on a pre-adolescent rural population, the Cronbach's alpha coefficient values for the applied questionnaire (MMORPG) and scale (SWLS) are satisfactory, which shows that the measuring instruments are adequate for research in the Serbian-speaking area. Exploratory factor analysis on a Serbian sample of pre-adolescents confirmed the 10-factor latent structure of the Motivation For Massive Multiplayer Online Role-Playing Game (MMORPG) Questionnaire. A ten-dimensional model of extracted factors (progression, game mechanics, competition, communication, relationship, teamwork, discovery, role-playing, character editing, and escaping reality) of motivation allows for the identification of inconsistent results on the effects on the subjective perception of well-being of video game players, as well as testing the negative and positive effects of playing online video games. The conducted multiple regression analysis determined that the motivation for playing entertaining video games explains more than 1/4 of the variability of the players' life satisfaction criteria, with a lower level of perceived life satisfaction being shown by players who entertain themselves to bring their character (armor) to a high level in color and style, with the distribution of unique items and pieces of equipment to achieve success, as well as players who entertain themselves to escape reality. In the prediction of dimensions of the life satisfaction construct based on a model of 10 motivation factors – factors progression (β = -0.52, p ≤ 0.01) and escaping reality (β = -0.48, p ≤ 0.01) manifested statistical significance, suggesting that they have a relevant role in predicting life satisfaction in pre-adolescents from rural areas. The findings of empirical research allow for the creation of interventions to form motivational factors to improve life satisfaction in pre-adolescents between the ages of 10 and 11.

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INTEGRATED SPATIO-TEMPORAL MODELING AND OPTIMIZATION OF GREENHOUSE GAS EMISSIONS AND URBAN AIR QUALITY BASED ON MULTI-SOURCE ENVIRONMENTAL OBSERVATIONS

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Abstract. Accurate monitoring and modeling of greenhouse gas (GHG) emissions and urban air pollution are essential for effective environmental management and climate policy. This study presents an integrated spatio-temporal framework for analyzing emission sources, optimizing observation networks, and predicting air quality using publicly available environmental datasets of high practical relevance. Three datasets were analyzed: (1) simulated GHG concentrations from 2921 grid cells in California using the WRF-Chem model, with synthetic observations and tracer-based decomposition; (2) meteorological variables (temperature, humidity, wind, geopotential height, sea level pressure, precipitation) across multiple atmospheric levels; and (3) real-world air quality and meteorological data from 12 monitoring stations in China (2010–2017). These datasets reflect both controlled (simulation-based) and real-world environmental conditions, enabling comprehensive testing of modeling approaches. A Bayesian inversion method was applied to estimate the optimal weights of GHG tracers contributing to synthetic observations, enabling source attribution. Sensor network optimization was addressed using a genetic algorithm to identify minimal configurations with high spatial representativeness. Predictive modeling of pollutant concentrations was performed using Random Forest and LSTM networks, with meteorological covariates as inputs. Missing values in time series were handled using KNN and regression-based imputation. All analyses were implemented in Python using open-source libraries, ensuring reproducibility and adaptability. The results demonstrate that combining simulated and observational data enhances source identification, while machine learning models informed by meteorological conditions provide robust short-term forecasts of air pollution. This framework offers a scalable, data-driven approach for supporting environmental monitoring, sensor placement, and early-warning systems in urban and regional settings.

Keywords: Greenhouse gases, inverse modeling, air quality prediction, sensor network optimization, environmental monitoring.

1. Introduction

Climate change and air quality degradation remain among the most pressing global environmental challenges. Accurate quantification of greenhouse gas (GHG) emissions and effective monitoring of urban air pollution are essential for designing mitigation strategies, assessing policy impacts, and safeguarding public health. However, both GHG source attribution and air quality forecasting are inherently complex due to the spatio-temporal variability of atmospheric conditions, the interplay of anthropogenic and natural sources, and the limitations of available observational networks.

This study addresses these challenges by integrating multiple open-access environmental datasets into a unified analytical framework that combines inverse modeling, optimization, and machine learning. Specifically, the goal is to (i) estimate the contribution of spatially distinct GHG sources to synthetic observations via inverse methods, (ii) optimize the placement of atmospheric observation points to maximize monitoring efficiency, and (iii) predict urban air pollution levels using meteorological covariates and time series models.

Three datasets of high scientific and practical relevance were selected:

- (1) A synthetic GHG dataset generated by WRF-Chem simulations across 2921 grid cells in California, containing 15 tracer signals and synthetic GHG observations. This dataset enables controlled validation of inversion techniques for source attribution.
- (2) A meteorological dataset with variables such as temperature, humidity, wind speed and direction, geopotential height, and precipitation measured across different atmospheric pressure levels. These variables are essential for understanding pollutant transport and dispersion.
- (3) A real-world dataset of hourly air pollutant concentrations and meteorological parameters from 12 urban stations in China (2010–2017), which serves as a testbed for evaluating predictive models under realistic conditions with missing data.

To analyze the data, a Bayesian inversion method is applied to estimate optimal tracer weights in the synthetic GHG dataset, while a genetic algorithm is employed to determine the optimal configuration of observation points. For air quality forecasting, Random Forest and Long Short-Term Memory (LSTM) models (Suman, N, et all, 2024) are trained on the urban dataset, with missing values handled using KNN and regression-based imputation methods. All models and procedures are implemented using open-source Python libraries, ensuring reproducibility and adaptability of the approach to other regions or pollutants.

2. Methodology

This section outlines the methodological framework used to (1) estimate the contributions of regional GHG sources to observed concentrations, (2) identify optimal locations for sensor deployment, and (3) forecast air pollution levels in urban areas using machine learning. All methods were implemented in Python using standard open-source libraries such as NumPy, SciPy, scikit-learn, TensorFlow, and DEAP.

2.1 Bayesian Inverse Modeling of GHG Tracer Contributions

To estimate the relative contributions of GHG tracers to synthetic observations in the WRF-Chem dataset, we employed a Bayesian linear inversion approach (Harris et all, 2024). This technique is well-suited for underdetermined or ill-posed problems where direct solutions are unstable due to limited or noisy observations (Zhou, 2024).

Let denote the vector of synthetic observations and a matrix containing 15 time series of GHG tracers from distinct spatial regions. The linear relationship is modeled as:

$$y = X\omega + \varepsilon \quad (1)$$

where ω is the vector of unknown tracer weights, and ε is the error term assumed to follow a Gaussian distribution. A Gaussian prior is placed on , and the posterior distribution is derived using Bayes' theorem:

$$p(\omega \mid y) = \frac{p(y \mid w) p(w)}{p(y)} \quad (2)$$

The posterior mean of ω serves as the estimate of tracer contributions. Regularization via prior variance helps control overfitting. This formulation allows uncertainty quantification and naturally integrates measurement noise.

2.2 Genetic Algorithm for Sensor Placement Optimization

To optimize the placement of observation points across the 2921 grid cells, we implemented a genetic algorithm (GA). The objective was to identify a minimal subset of grid cells that allows accurate reconstruction of the full GHG field using the tracer model. To optimize the placement of observation points across the 2921 grid cells, we implemented a genetic algorithm (GA) (Barklage et all, 2024). The objective was to identify a minimal subset of grid cells that allows accurate reconstruction of the full GHG field using the tracer model. Each chromosome in the GA represents a binary vector indicating selected grid cells. The fitness function is defined as the inverse of the reconstruction error (e.g., mean squared error between actual and reconstructed GHG observations). Standard GA operations—selection, crossover, and mutation—are applied iteratively to evolve a population of solutions toward optimal sensor configurations (Zhang et all, 2025).

This method is advantageous due to its ability to search large combinatorial spaces and avoid local minima, making it suitable for real-world spatial optimization problems.

2.3 Predictive Modeling of Urban Air Pollution

To model urban air pollution levels, we used two supervised learning approaches: Random Forest Regression and Long Short-Term Memory (LSTM) neural networks (Yang, Y. et all, 2025). These models were trained on the Chinese urban air quality dataset, which contains hourly measurements of pollutants and meteorological parameters from 2013 to 2017.

- Random Forest was chosen for its robustness to noise, interpretability (via feature importance), and ability to handle nonlinearity.
- LSTM was used to capture temporal dependencies and lag effects in the time series data, which are critical for modeling pollution episodes.

The input features included wind speed and direction, temperature, humidity, pressure, and precipitation. The target variables were PM2.5 and other pollutants.

Missing data were imputed using a combination of K-Nearest Neighbors (KNN) and regression imputation, depending on variable type and missingness pattern. Feature selection was performed using correlation analysis and permutation importance.

Models were evaluated using RMSE, MAE, and metrics on hold-out test sets (Ding, J, et all, 2024).

3. Data and Preprocessing

Three distinct datasets (UCI: https://archive.ics.uci.edu/dataset/328/greenhouse+gas+observing+network, https://archive.ics.uci.edu/dataset/501/beijing+multi+site+air+quality+data, https://archive.ics.uci.edu/dataset/381/beijing+pm2+5+-data) were used to support the multi-objective analysis conducted in this study (Lucas, D., 2025; Chen, S., 2017; Chen, S. 2015). Each dataset was subjected to tailored preprocessing workflows to prepare it for subsequent modeling and optimization.

3.1 WRF-Chem Synthetic GHG Dataset (California, 2010)

This dataset contains simulated greenhouse gas (GHG) concentrations across 2921 grid cells in California, produced using the Weather Research and Forecasting model with Chemistry (WRF-Chem). Each file contains 16 time series: 15 synthetic tracers representing emissions from distinct spatial regions and one synthetic observation signal, generated by scaling EDGAR emissions of HFC-134a with additive noise. Each time series consists of 4 samples per day from May 10 to July 31, 2010 (≈ 330 values per series).

All files were loaded and synchronized based on temporal indices. Time series were standardized (zero mean, unit variance) prior to inversion modeling. The dataset's design allows a known "ground truth" to be inferred, which is ideal for testing source attribution algorithms.

3.2 Meteorological Attribute Dataset

This dataset contains meteorological measurements at multiple pressure levels (850 hPa, 700 hPa, 500 hPa), including:

- Temperature (T_AV, T_PK, T85, T70, T50)
- Wind speed and components (WS_AV, WS_PK, U/V at 850/700/500 hPa)
- Humidity, geopotential height, sea level pressure (SLP), precipitation, and derived stability indices (K-index, T-totals)

This data exhibited missing values across several attributes. Missing values were imputed using K-Nearest Neighbors (K=5) for continuous variables. Attributes were normalized for machine learning models and filtered using correlation analysis to reduce redundancy.

3.3 Air Quality and Weather Data (China, 2013–2017)

This dataset includes hourly pollutant concentrations (e.g., PM2.5, PM10, NO2, O3) and meteorological parameters collected at 12 monitoring stations in China. The data spans four years (March 2013 – February 2017) and is characterized by nonstationarity, seasonal variation, and missing data (denoted as NA).

We applied rolling window aggregation (3h, 6h, 12h means) and time-based lag features (t–1 to t–24) to capture temporal dependencies. Missing data were imputed using multivariate regression for pollutants and linear interpolation for weather parameters. Data were split chronologically into training (80%) and testing (20%) sets.

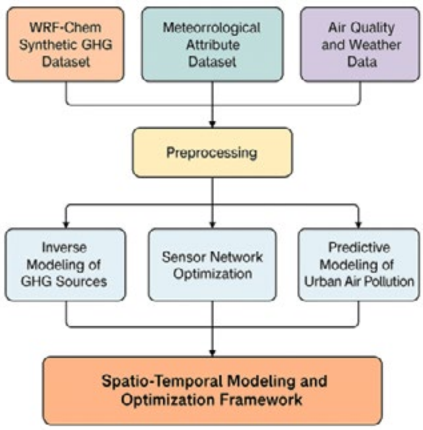

Figure 1. Overview of the spatio-temporal modeling and optimization framework integrating greenhouse gas simulations, meteorological variables, and urban air quality data. The framework includes data preprocessing, inverse modeling of GHG sources, sensor network optimization, and predictive modeling using machine learning.

4. Results

Table 1 presents a comparative summary of the predictive performance of three distinct modeling tasks: (1) PM2.5 forecasting using LSTM networks, (2) stock price prediction using a Random Forest Regressor, and (3) ozone level classification using Random Forest and imputation-based preprocessing. The performance is evaluated using standard regression metrics—Mean Absolute Error (MAE), Root Mean Squared Error (RMSE), and Coefficient of Determination (R^2)—for the regression tasks, while ozone classification performance is interpreted via F1-score and feature contribution analysis.

Table 1. Model Performance Table

Model	MAE	RMSE	R^2
PM2.5 Forecasting	56.84	80.07	0.279
Stock Price Prediction	7.92	13.25	0.857

Figure 2 shows comparative boxplots of prediction errors for two modeling tasks: PM2.5 concentration forecasting and Stock price prediction. The y-axis in both plots represents the raw prediction error where values above zero indicate underprediction and values below zero indicate overprediction.

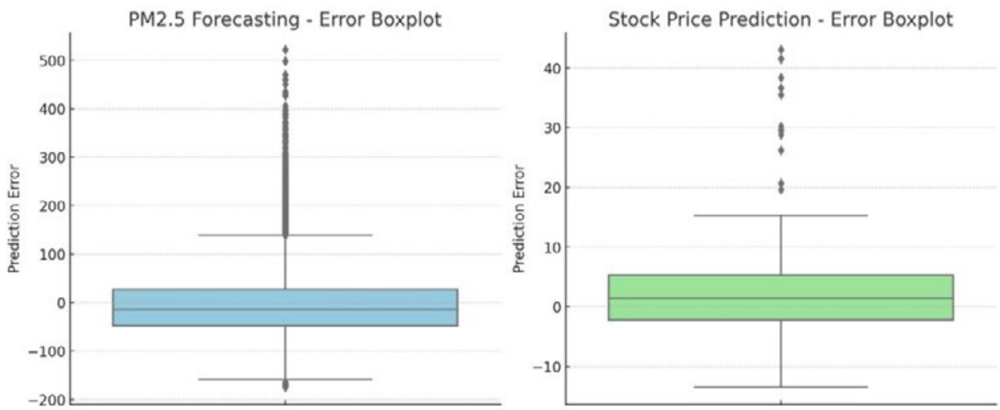

Figure 2. PM2.5 concentration forecasting using Long Short-Term Memory (LSTM) networks. (Left) Stock price prediction using Random Forest Regressor. (Right)

The error distribution for PM2.5 forecasting is negatively skewed, with a peak around 0, indicating that the model generally performs well. However, there is a long left tail, meaning the model underpredicts PM2.5 concentrations more often and more severely than it overpredicts. The majority of predictions are within ±50 µg/m³, but extreme errors go beyond ±200 µg/m³, showing sensitivity to high pollution episodes.

The Random Forest model was employed to assess the contribution of individual features to PM2.5 concentration prediction. As visualized in Figure X, a sharp drop in importance is observed after the top few features. Variables labeled F40, F38, and F30 show the highest importance scores, each contributing over 3–8% to the model's predictive power. These likely correspond to atmospheric variables such as wind direction components, temperature, and humidity, which are known to influence particulate dispersion and accumulation.

The long-tail distribution of feature importance suggests that a smaller subset of variables holds most of the explanatory power. This supports the potential for dimensionality reduction techniques in future work, either through feature selection or embedding. Moreover, understanding which meteorological drivers are most influential can support targeted sensor deployment and policy decisions aimed at mitigating pollution episodes (Figure 3.).

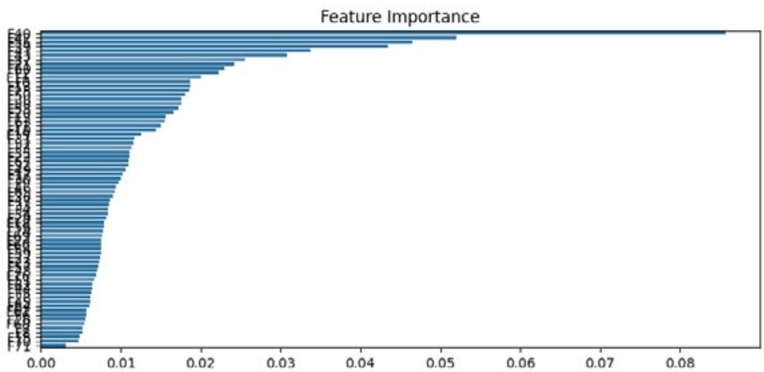

Figure 3. Feature importance ranking for PM2.5 forecasting based on Random Forest regression. Features F40, F38, and F30 dominate the model, indicating strong predictive power likely associated with meteorological variables such as wind direction and temperature.

Figure 4 illustrates the relative importance of input features used by the Random Forest model in predicting stock closing prices. The “Low” price was the most influential variable, contributing over 40% to the model’s decision-making process. This is followed by the “High” and “Open” prices, contributing approximately 33% and 27%, respectively. In contrast, the “Volume” of traded shares showed negligible influence on model output.

These results align with financial intuition, as daily high, low, and open prices are tightly coupled with the closing price through market microstructure dynamics. The minimal influence of volume suggests that price dynamics alone provided sufficient predictive signal, potentially due to the relatively stable trading patterns in the analyzed period. This finding reinforces the value of price-driven features in short-term forecasting tasks and suggests that volume may only play a greater role in models addressing volatility or liquidity prediction.

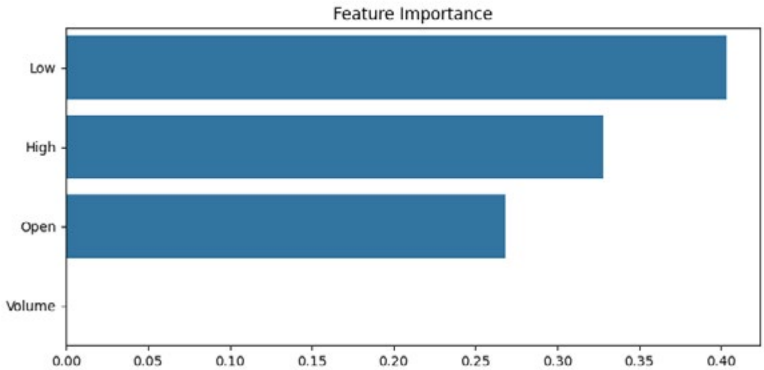

Figure 4. Feature importance analysis for stock price prediction. The "Low" price feature had the highest predictive contribution, followed by "High" and "Open" prices, while "Volume" contributed negligibly to the model.

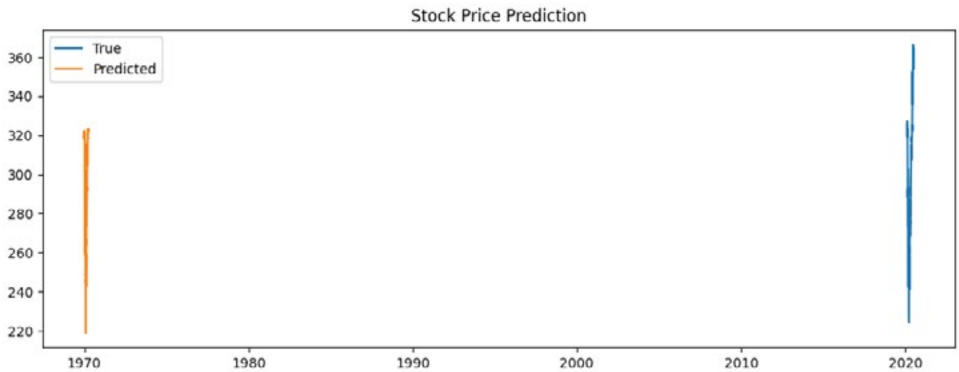

Figure 5. Stock Price Prediction — Time-series comparison of actual vs. predicted stock closing prices using a Random Forest regression model. Note: Temporal axis distortion is present due to missing or misformatted datetime indices in the input data. Despite this, the vertical value alignment reveals strong predictive accuracy in terms of price level estimation.

Figure 5. presents the model's performance in forecasting stock closing prices. Although the temporal alignment on the X-axis appears misaligned — likely due to improper datetime formatting or index preservation during preprocessing — the comparison between the true and predicted prices remains valid in terms of magnitude alignment.

The Random Forest model demonstrates a high level of fidelity in capturing the stock price dynamics, particularly in maintaining the overall value distribution and short-term variations. This is also supported by the relatively low RMSE and high R^2 obtained in earlier evaluation.

The visualization in Figure 6. illustrates the forecasting performance of the LSTM model applied to hourly PM2.5 concentration data. The blue line represents the true measured values, while the orange line denotes the model's predictions.

Although the model demonstrates satisfactory performance in capturing broader seasonal trends and baseline variability, it underperforms during high-concentration events. These peak underestimations are particularly visible in the early and late parts of the series, which may coincide with winter heating or localized emission episodes. This systematic bias suggests that while LSTM is adept at modeling temporal dependencies, it may require enhancement through attention mechanisms, event-specific variables, or ensemble strategies to better predict outliers.

Moreover, the predictive smoothness of the LSTM output indicates strong regularization, which can be beneficial for generalization but detrimental when precision in episodic events is needed — a common trade-off in environmental time-series forecasting.

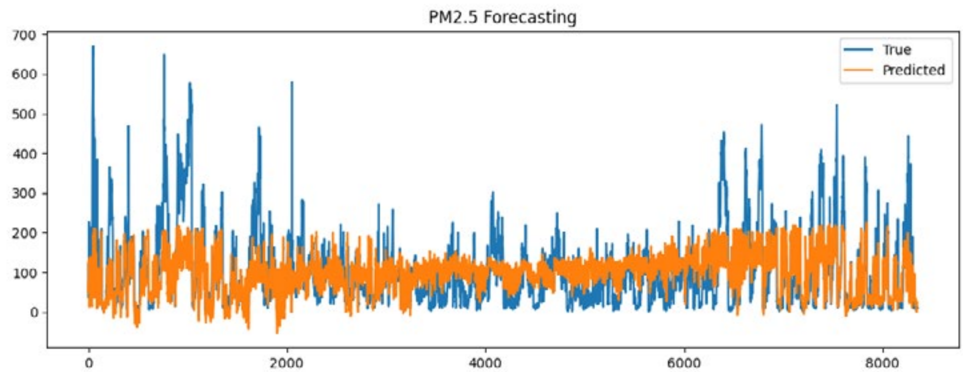

Figure 5. PM2.5 Forecasting — Comparison between true PM2.5 values and predicted values generated by the LSTM model. While the model captures general trends and seasonal fluctuations, it systematically underestimates extreme spikes, indicating limitations in representing sudden pollution events.

This discrepancy emphasizes the need for either hybrid modeling or inclusion of external covariates (e.g., emission events, holidays).

5. Discussion

This behavior is expected in environmental time-series data with sudden pollution spikes (e.g., due to temperature inversion or industrial events), which are harder to predict using historical data alone. The underprediction during high pollution periods could be addressed by:

- Integrating event-based features (e.g., holidays, fires, construction).
- Using hybrid models or attention mechanisms in LSTM architectures.

The stock price model appears more stable, which may reflect the use of lag features and smoother trends in the test window. However, the outliers suggest the model could not adapt quickly to abrupt market changes, which may be due to:

- Lack of external signals (e.g., news, earnings reports).
- The use of historical-only features (Open, High, Low, Volume).

Improvements could include:

- Sentiment analysis inputs, technical indicators, or exogenous data streams.
- Ensemble models or attention-based transformers.

6. Conclusion

These results confirm that data quality and domain complexity strongly influence predictive success. While stock market dynamics are captured effectively by tree-based models using clean historical data, air quality forecasting remains more challenging due to spatio-temporal variability and unobserved external influences. The ozone classification task requires dimensionality reduction or regularization for better model clarity. Collectively, these findings support the adoption of tailored preprocessing and model architectures for each domain.

This work demonstrates that machine learning, statistical inversion, and evolutionary optimization can be synergistically applied for practical tasks in environmental data science and time series analysis. Importantly, the framework remains scalable, reproducible, and adaptable to other pollutants, urban areas, or geophysical settings, enabling its integration into operational decision-making systems such as smart city dashboards, early warning systems, or climate planning tools.

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SMOOTHING OF DRAFT FORCE SIGNAL DURING PLOWING BY SAVITZKY - GOLAV FILTER

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Abstract: The measurement of draft force and soil resistance during plowing can be performed using a strain transducer. They are placed on the lower tractor links, two sensors on each side. After calibrating the sensors, acquiring and processing the data, the draft force Fout and Fin are obtained, which correspond to the measurements on the two sensors on the outside of the arms and the measurements on the sensors on the inside of the lower links. Extreme values of the force signal as a function of time are extremely pronounced due to changing conditions during the measurement. This paper investigates the influence of one of the possible Savitzky-Golav smoothing signal filters. First, the appearance of the force maps is shown in the experimental field of dimensions 120x60 on which the force effect is most uniform. The corresponding diagram is also given with a display of the signal based on the sensor measurements. Then, the data is filtered and the appearance of the new signal diagram is given. Descriptive statistics finally provides a measure of the influence of the applied filter. Statistical parameters have shown that the influence of the investigated filter is minimal.

Key words: draft force, strain transducer, filter, mapping, Savitzky-Golav smoothing

1. INTRODUCTION

There are several methods for defining the Rx horizontal draft of the tractor attach ment. Horizontal draft varies depending on the method of soil tillage, size of attachment and implement, speed of motion and soil type. A number of methods have been developed for analytical evaluation of the attachment draft. Based on theoretical considerations and experiments, Goryachkin [1] developed an equation for the plough horizontal draft evaluation:

$$R_x = Gf + kabn + \varepsilon abnv^2 \tag{1}$$

The first term of this equation is frictional resistance, where, G [N] represents plough weight and f (-) is coefficient of friction. Average value of the coefficient of friction is in the range of 0,3–0,5 [2], however it can have higher value for compact soils. The second term is the force required for cutting and deforming of a clod. Coefficient k [N/m^2] is soil specific resistance that depends on the soil type [3] parameter a [m] is plowing depth, third term of the equation denotes the force required to bring clod into motion and turn it over. Coefficient ε [Ns^2/m^4] depends on the plough body shape, soil properties and tractor speed v [m/s]. This term increases as speed is increased. For speeds up to 5 km/h the value of the third term does not exceed 5% of the overall plowing resistance. Recommended plowing speeds are in the range of 5–10 km/h to achieve satisfactory plowing quality. Value of the coefficient ε ranges from 3000 to 10 000 Ns^2/m^4 [4]. The impact of plough geometry on horizontal draft is given via the plough body width b. To precisely define the impact of geometry, an experiment has to be conducted [3].

Based on data presented in considering the assumptions and adopted parameters' values as follows: $f = 0{,}5$; k = 5000 N/m^2 (medium heavy soil – sandy clay); $\varepsilon = 5000$ Ns^2/m^4, approximate value is obtained for the plough draft and tractor pulling force, respectively, which is used in the mapping procedure 9515 kN for the tillage depth of 20 cm.

2. MATERIAL AND METHODS

Key elements of the system used for indirect measuring the values of the plough draft force in this research were strain transducers. Theses sensors are installed on the lower links of the tractor lift mechanism. Sensors were placed on both sides of the two lower links facing each other longitudinally. Strain transducers of the HBM manufacturer model SLB700A/06 are designed purely to measure static and dynamic strains within the load limits. The measurement signal from the sensor is received and processed by means of the amplifier, manufacturer HBM, model Quantum MX840A.

Location positioning equipment of the manufacturer AG Leader Technology included the antenna model GPS1600 for Egnos signal reception and tractor monitor model Integra for monitoring the motion of the tractor-machine unit. The antenna signal was simultaneously introduced directly into the computer via a specially designed adapter. Data was stored, visualized and afterwards analyzed using software CatmanEasy 4.2.2.14, manufacturer HBM. Additional data processing was done with software SPSS Statistics 21 from IBM, for statistical data analysis and SMS Advance from AG Leader Technology for mapping.

Raw results for lower links strain measurements represent strain signals on the strain transducers. Prior to measurement, zero balance of all sensors was done while tractor was in an idle state with a plough lowered to the ground. Data was collected during plowing with the measurement resolution 50 Hz. This way, 195 040 strain values were collected for each individual sensor.

3. RESULTS AND DISCUSSION

The results of draft force measurements can be presented in several forms. In practice, the most common way is through force maps, which show the site-specific force distribution (Figure 1) and are used to determine input application maps based on the princi-

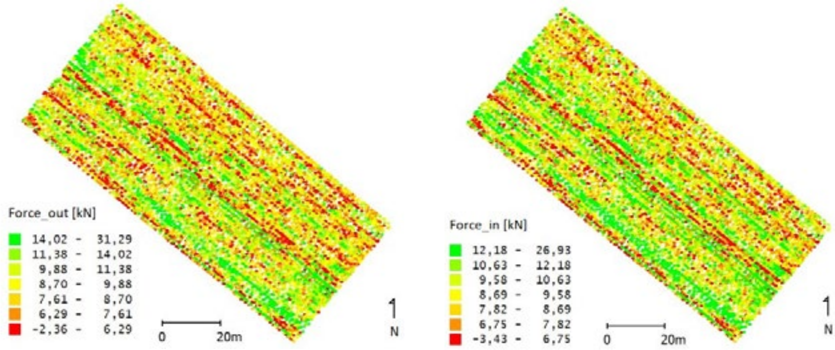

Fig. 1 Representation of site-specific draft force, kN, software SMS Advance by AG Leader Technology

The maps shown are obtained based on the numerical values of the measured force, the values of which are obtained by calculation in accordance with the calibration of the strain transducers. The measured forces using pairs of sensors from the outer and inner sides of the levers can be displayed in the time domain (Figure 2). The diagrams, as well as the numerical values of the forces, show their correlation for both measurement methods, so it can be concluded that the sensors can be placed either on the outer or inner side of the levers. Significant oscillations and frequent changes in amplitude can be observed on the representative real-time graphs of pulling force, so the use of filters is quite useful from this aspect.

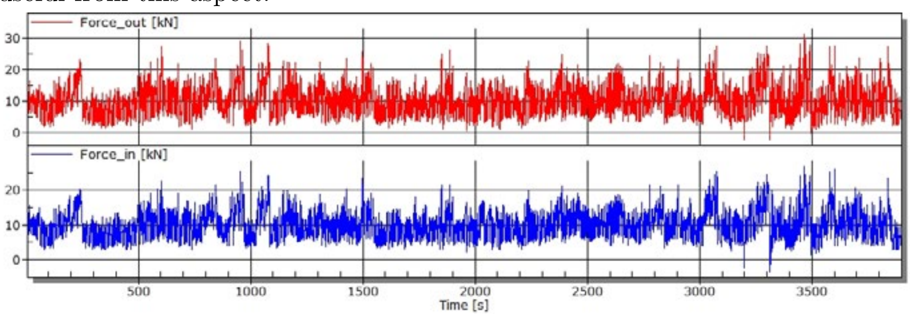

Fig. 3 Representative real-time graphs of draft force by Savitzky-Golay filtering

	N	Minimum	Maximum	Mean	Std. Deviation
Force_out	195040	-2,356	31,290	9,863	3,795622
Force_in	195040	-3,430	26,930	9,868	3,175271
Force_out_filter	195040	-2,343	30,765	9,863698	3,767148
Force_in_filter	195040	-3,422	26,659	9,868082	3,147096
Valid N	195040				

Statistical indicators do not show a significant difference between the original and filtered relevant force values.

4. CONCLUSIONS

For mapping of draft force and soil resistance and consequently soil compaction by applying the described method, two sensors are sufficient. Average value of forces Fout and Fin is approximately very equal for given conditions and in given measured range, therefore either only outside or only inside sensors can be employe [14, 15]. Output voltage signals on sensors installed on the same links are of similar absolute values but different sign. Signal diagrams and statistical analysis have shown a significant need for data filtering. This way, too large amplitudes of output voltage and draft force can be avoided and thus more reliable maps obtained. The Savitzky-Golay filter is not a necessary tool and does not change the picture of the location specificity of the draft force.

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THE CALIBRATION PROCESS OF THE "TRIMBLE - YIELD MONITORING" SYSTEM FOR THE PURPOSE OF YIELD MAPPING DURING THE TECHNOLOGICAL OPERATION OF BARLEY AND WHEAT HARVESTING

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Abstract. The integration of various technologies such as sensors, GPS, drones, collection, analysis and management of data obtained during agricultural production is the standard when it comes to precision agriculture. Yield, as the main goal of production, is not just the value after harvest, but says much more when yield data is appropriately collected and later analyzed in the right way. Mapping involves collecting yield data from different locations on the plot and creating a map or spatial representation of yield variations. This provides an insight into the heterogeneity of the plots is obtained and the right decisions can be made and activities on the plots can be planned appropriately. The experiment was carried out in the technological operation of harvesting barley and wheat at the sites Progar and Padinska Skela, owned by the company "Al Dahra". A combine harvester "New Holland CR 7.90" was used for harvesting with a "Trimble Yield Monitoring System" to monitor and map yields. The system is equipped with an optical sensor to monitor the applied mass and a moisture sensor "Ag Leader". During the work, the following parameters were monitored: moisture, amount of mass harvested, hectoliter mass, and a calibration of the entire system was performed to minimize the possibility of errors.

Keywords: precision agriculture, GPS, mapping, yield, harvest, harvester, calibration.

1. INTRODUCTION

Harvesting is the last technological operation in the cycle of agricultural production, during which information about the quantity and quality of the threshed grain can be obtained. Timely harvesting and the use of appropriate technical means are essential for the implementation of the entire process, i.e. for maximizing productivity and minimizing losses of threshed grain. The technological aspect of harvesting has reached a fairly high level, the technical means used produce minimal losses, the operator's work is based on the use of various technical systems. As in other production segments, the term precision farming is often heard in this area. The advantages of using this technology do not stop at harvesting, so that many of the new technologies can also be used in this process [2, 5].

Tractors can be equipped with autopilot systems with RTK signals for sowing, feeding and crop protection, and combine harvesters are equipped with the same systems. With an accuracy of 2.5 cm and the ability to monitor the work process in real time, an enviable level of production was achieved. With the eternal pursuit of higher yields and better working conditions, man has created some systems that greatly facilitate the work of the agricultural producer. One of the applied systems in agricultural production technology is the ability for the operator to monitor the crop yield in real time during harvest. If we combine systems such as yield monitoring during harvesting and GPS technology, we get the possibility to record the yield quantities per certain unit of area [1, 9, 11].

Trimble has developed a standardized system for monitoring and mapping yields - the "Yield Monitoring System". It enables us to create a separate yield map for each plot on which we harvest. By mapping the entire process from sowing to feeding, protection and harvesting, we can carry out a detailed analysis that allows us to make better decisions throughout the process. By using this system, we can achieve considerable savings in the use of the various inputs. The savings are reflected in the fact that, based on the analysis of the yield maps, vegetation indices and soil analysis, the standards for sowing and top dressing have been reduced and thus savings have been made, as well as in the database on the quality of the soil we have [4, 7, 8].

To achieve accurate results, the system must be properly calibrated and its accuracy must be monitored during operation. The aim of the study is to monitor the calibration process of the yield mapping system, its accuracy and the possibilities we have with the collected crop data. During the test, the entire process was followed, from the installation of the system itself to its commissioning and calibration, i.e. achieving the highest possible accuracy.

2. MATERIAL AND WORKING METHODS

The calibration of the yield mapping system was carried out on combine harvesters of the manufacturer "New Holland", model "CR 7.90", during the technological operation of the barley and wheat harvest. The site where the calibration process was carried out is located near Progar (44.708889, 20.156944) and Padinska Skela (44.939722, 20.424444), on plots belonging to the company "Al Dahra". The test was carried out on several plots with a total area of 50 ha.

The mapping system tested is a system from the American manufacturer Trimble "Yield Monitoring", which can optionally be added to the existing autopilot system with the navigator "TMX 2050" (Fig. 2.a) (Tab 1.) from the same manufacturer. The hardware part consists of an optical sensor (Fig. 1.a), which measures the grain level on the threshing unit, and the moisture sensor "Ag Leader" (Fig. 1.b), as well as the software application "FmX Plus" (Fig. 2.b), also developed by Trimble [6, 9].

Figure 1. (a) Optical sensor that measures the fill level at the blades of the mass elevator (b) Ag Leader moisture sensor

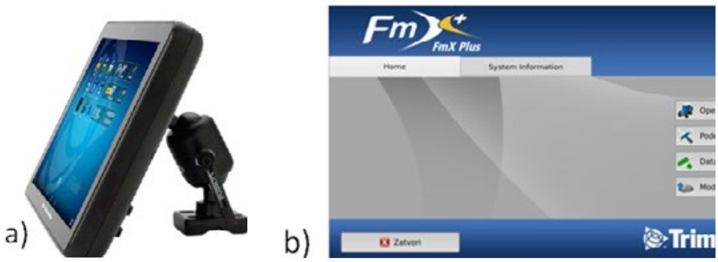

Figure 2. (a) Trimble TMX 2050 navigator (b) FmX Plus software for use with the Yield Monitoring system, [9]

Table 1. Technical characteristics and functionalities of Trimble TMX 2050 navigator

Technical features	
Display	Touchscreen, 30.8 cm diagonal, high resolution
Operating system	Android operating system
Internal memory/RAM	16 Gb/ 1Gb
Navigation software	FmX Plus / Precision IQ
GNSS receiver	Dual frequency
ISOBUS compatibility	Yes
Optional camera output	Yes
Storage of	users / properties / packages / handlers / operations
USB port	Yes

Functionalities	
Automatic steering	Trimble Autopilot/EZ-Pilot/EZ-Steer/TrueTracker/TrueGuide
NextSwath (headland turning)	Yes
AutoSync (wireless data exchange)	Yes
Precise application of nitrogen fertilizer	Yes
Yield and moisture monitoring	Yes
Checking the leveling of plots	Yes
Mapping of boundaries and objects on plots	Yes

In this research, the yield monitoring and mapping system used in a New Holland combine harvester was powered by an 8.7-litre inline six-cylinder engine with a "common rail" fuel injection system controlled by an electronic control unit (ECU). The transmission is hydrostatic, 4 gears (forward and reverse). During the test, the combine harvester was mounted with a wheat header.

Table 2. Technical features of the harvester

	Paremeters	Units	
1.	Number of cylinders / charging	/	6 / turbo
2.	Engine power	KW	338
3.	Nominal engine speed	rpm	2000
4.	Engine displacement	ccm3	8709
5.	Max. speed	km/h	30
6.	Type of transmission	/	Hydrostatic 4+4
7.	Weight of vehicle	kg	18000
8.	Dimensions	m	3,25/9,97/3,97
9.	Type of movement system	/	Wheel
10.	Grain tank size	l	9500
11.	Emission class	/	V

As part of this research, an additional "Yield Monitoring" system was installed on the existing Trimble TMX 2050 Autopilot system to monitor data on the amount of mass harvested and the moisture level at the time of harvest. The harvester's navigation device is equipped with software for yield mapping and real-time monitoring of harvesting parameters during harvesting. The application used during harvesting is FmX Plus.

The system consists of the following components:

- Moisture sensor (Figure 1b): It generates an electric field, detects disturbances due to changes and changes the capacitance in the dielectric material around the sensor. Changes in capacitance result in changes in the output voltage signal that is sent to the yield monitor.
- Proximity switch (Figure 1a): Controls the level of grains in the sensor housing. It reacts to the presence of grains in a certain zone and sends a signal to a DC motor that drives the elevator to empty the moisture measurement system housing. It works on the principle of changing the value of the dielectric constant, which is 1 for air, compared to grain, whose constant value is between 10 and 30.
- Header height sensor (Figure 3c): Provides information about the height of the crop header based on which cover detection is turned on or off, i.e. whether or not to harvest at a given time.
- Spiral conveyor (Figure 4c): It is used to empty the cover; when the proximity sensor sends a signal to it, it is activated and the mass that was in the sensor is conveyed further to the elevator and the bunker, freeing up space for receiving new grain and for repeated measurements.
- DC motor (Figure 4b): It drives the spiral conveyor and is activated by the signal from the proximity sensor.

Figure 3. (a) Moisture measurement system (b) moisture sensor (c) header height sensor

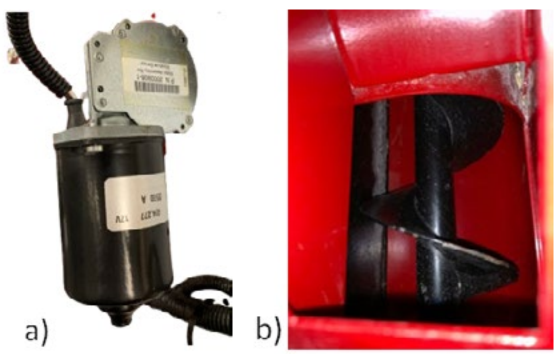

Figure 4. (a) DC motor (b) spiral conveyor

The Ag Leader system for moisture measurement is installed on the outside of the tunnel through which the blades of the threshed grain elevator move. The installed system has two openings on the tunnel through which the mass enters the space where the moisture sensor is located and through which the spiral conveyor returns the mass on which the moisture was measured back to the mass conveyor. The second part of this system is an optical sensor. It is also located on the outside of the tunnel through which the threshed grain elevator moves and its task is to provide us with data on the amount of yield. The operating principle of this sensor is based on changing the parameters of the optical signal, i.e. each time the knife passes over, the sensor reads the size of the husk formed by the driven mass (Fig. 5). Based on the hectoliter mass and the size of the cup, the software calculates the yield and displays it on the screen of the navigation device in the cab [9].

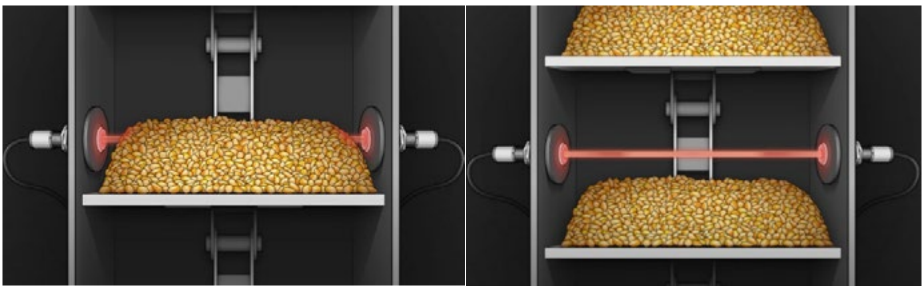

Figure 5. Functional principle of the optical sensor for monitoring the amount of threshing mass [9]

3. SYSTEM ADJUSTMENT AND CALIBRATION PROCESS

In order for the Trimble Yield Monitoring and Mapping System to perform its function properly, it is important that all system components are correctly connected and adjusted on the harvester. The entire process is controlled via the FmX plus application on the Trimble TMX 2050 navigator. In the application, the crop being harvested and the combine's work input must be set and the function of all sensors must be checked so that the further process of calibration and adjustment can begin [9].

Figure 6. (a) Home page of the FmX plus application (b) Configuration of the header

The first setting option is the "Implement" item (Fig. 2 (b)), in which we define the operation we are performing, the working handle of the header and its position in relation to the navigator's receiver. This item (Fig. 7) is very important for the accuracy of the mapping, so the correct measurements, i.e. the physical dimensions of the cutting unit and the dimensions of the application itself, must be entered so that the navigation system can form the correct navigation lines.

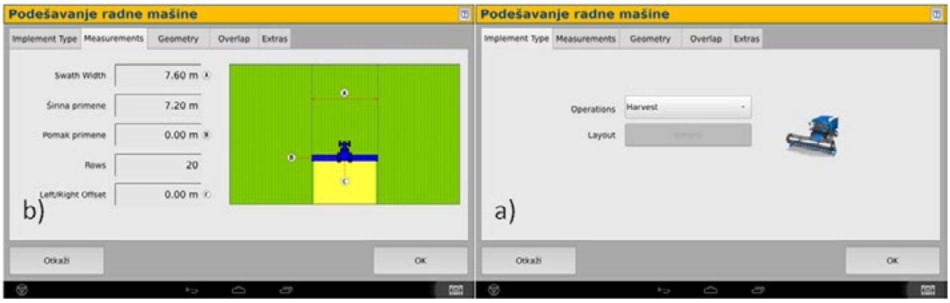

Figure 7. (a) Selection of the operation (b) Settings of the working machine

After setting up the implement in the navigator, the next step is to select the Yield Monitoring module, which has several options in its menu, such as settings, calibration or diagnostics. In the basic settings (Fig. 8) for yield monitoring, the requirements for the system to function must be met, i.e. the following must be selected: the manufacturer of the combine harvester, its series, the type of yield monitoring and the type of moisture sensor. The next step is the "Advanced settings" option (Fig. 9), where the dimensions of the blades of the pure grain elevator must be entered, which pass the previously installed optical sensor, which is placed in a suitable position.

Figure 8. Yield tracking settings with advanced options

To obtain accurate readings, it is necessary, after entering the dimensions of the blades, to enter the angle of the elevator and its compensation, if any. The compensation refers to the position of the buckets left-right or front-rear. If some of these parameters are not entered correctly, precise yield data cannot be obtained and there is also a possibility that an error will be reported during the initial calibration.

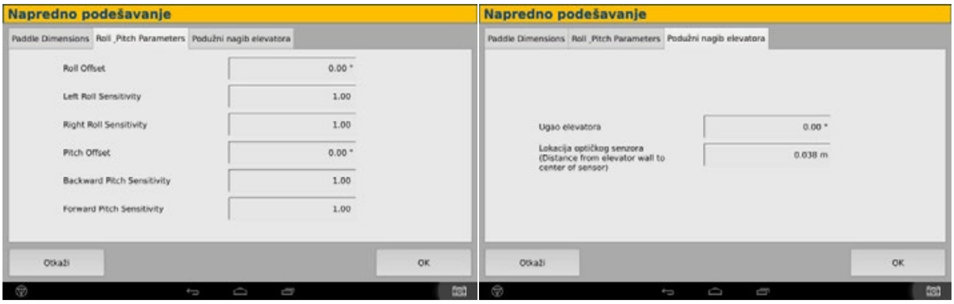

Figure 9. Entering the value of the elevator angle and its compensation

After entering data within the basic settings required for yield control (Fig. 10), it is necessary to adjust the height of the adapter (header). The setup can only be run if the height sensor is active, for which there is an indicator in the setup menu. After checking the activity, the highest and lowest position of the adapter is read and the distance between them is displayed as a percentage, 0% - the lowest, 100% - the highest position. During harvesting, these values are always visible on the navigator screen, depending on the position of the header. The next setting is of the time type and consists in measuring and then entering the time between the moment when the adapter mows the crop and the moment when the first grain falls into the combine's hopper. The following settings must also be entered: type of crop to be harvested, unit of measure, storage moisture and upper moisture limit.

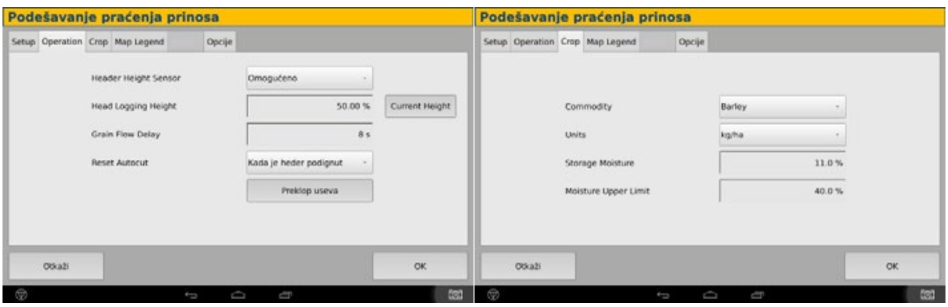

Figure 10. Header height setting, grain transit time from mowing to bunker, input of crop type, moisture values

To obtain accurate readings, it is necessary, after entering the dimensions of the blades, to enter the angle of the elevator and its compensation, if any. The compensation refers to the position of the buckets left-right or front-rear. If some of these parameters are not entered correctly, precise yield data cannot be obtained and there is also a possibility that an error will be reported during the initial calibration.

In the working view on the navigator's screen, the yield map is displayed according to the traffic light principle, with a good yield on a certain part of the bar cell being displayed in green and a poor yield in red, while the values between the upper and lower limits are displayed in yellow (Fig. 15). Accordingly, we adjust the upper and lower expected values of moisture and yield to accurately represent the coverage detection, i.e. the state of the yield on the plot.

Figure 11. Setting the coverage record on the working view

The next step is to calibrate the height of the adapter (header) and the yield sensor. Calibrating the height of the adapter (header) is necessary due to the voltage range in which the sensor operates, because if it is set to a mowing height that is outside the voltage range, the system will detect an error. Yield sensor calibration is performed to determine if there are certain deviations in the clean grain elevator mechanism, such as defects in the chain that carries the blades, missing or damaged blades themselves.

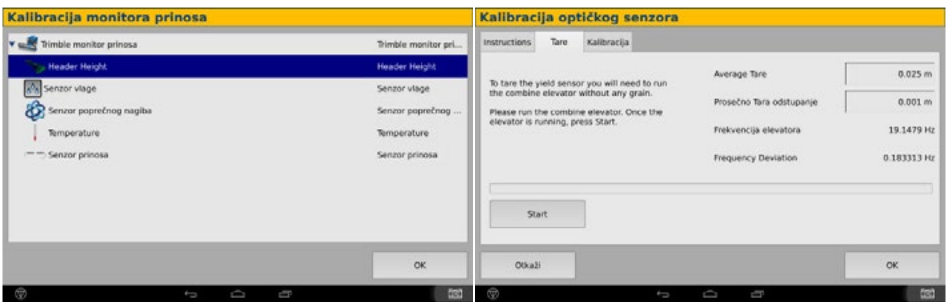

Figure 12. Selecting the settings in the yield monitor and calibrating the optical sensor

Calibration of the optical sensor (Fig. 12) is carried out by switching on the threshing unit according to the settings previously made, setting the number of revolutions to the maximum value and then obtaining data on the deviation and frequency of the elevator are obtained. The process is repeated three or more times, if the obtained (first and second decimal places) are not extremely different, the calibration is successful, and if the values differ by a whole number or more than 0.3 after each start, it is necessary to check the combine or elevator system.

Header height calibration (Fig. 13) is performed by pressing the "Start" button, after which the adapter is raised to the top position and 100% is entered in the first field, which represents the maximum height of the adapter. The adapter is then lowered to the lowest position, i.e. to the ground, and 0% is entered in the second field.

Figure 13. Header height calibration

The yield monitoring diagnostics (Fig. 14.) is used to check the yield monitoring status, header height, elevator angle, moisture percentage and other parameters during operation. The activity of the optical sensors can also be monitored, such as the percentage of darkness, which lets us know if the sensor is placed correctly, as well as the activity of the moisture sensor.

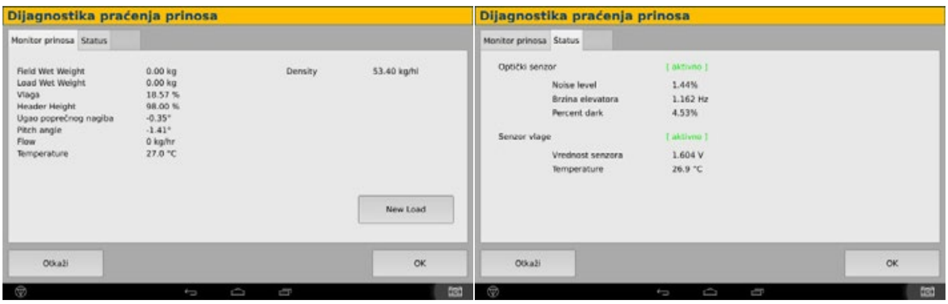

Figure 14. Yield monitoring diagnostics

The working view is used to monitor all parameters during operation, in it a new measurement called "load___" can be started (Fig. 15 (a)), in the same window the percentage moisture content as well as the average yield per hectare and the amount of harvested crop in a particular measurement can be monitored. In the "loads and calibration" option (Fig. 15 (b)), you can enter the density (hectoliter weight) and thus calibrate the yield sensor, and by entering data on the moisture percentage, you can calibrate the moisture sensor and thus obtain precise results for subsequent measurements.

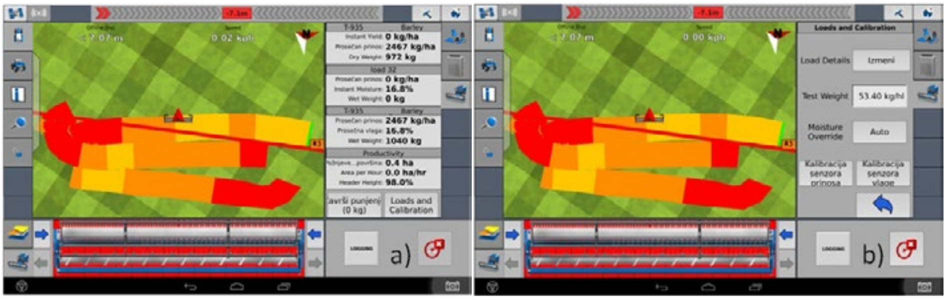

Figure 15. (a) Working view (b) Entering the correct values after checking in the precision measuring probe

Once the bunker for the crushed mass has been filled, it is transferred to a transport vehicle in which the grain is sent for inspection, i.e. for remeasurement with calibrated equipment. The harvester continues the harvest, i.e. with a new measurement of "load__ __", and one waits for the results of the accurate measurements, which are entered into the system as "load __ __" measurement data. If accurate measurement data is available, pressing the "Calibrate yield sensor" button (Fig. 15) opens the menu for entering values (Fig. 16). Under the "Calibration type" option, "Multiload" is selected, i.e. when calibrating multiple loads, the measurement results are checked by the mapping system and compared with the actual measured values. The measured value from the display is entered in the "Recorded Weight" field and the measured value from the calibrated scales is entered in the "Current weight" field, according to which the calibration is updated; it is also important to enter the hectoliter mass measured on the reference device in the "Test Weight" field in kg/hl. The system applies the updated calibration retroactively to both the previous and the next measurement.

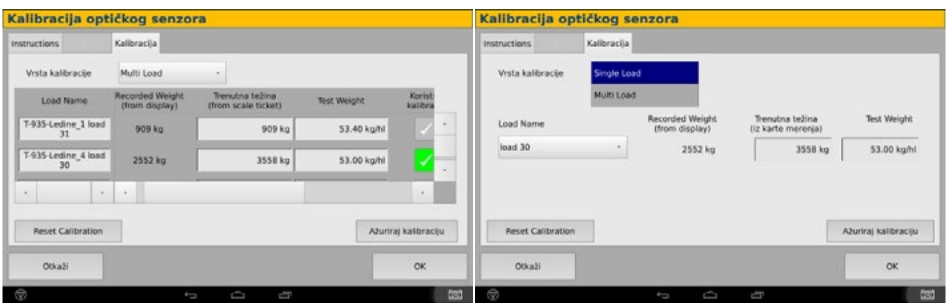

Figure 16. Yield sensor calibration menu

Calibration of the humidity sensor is started by pressing the "Calibrate humidity sensor" button (Fig. 17), which opens the calibration menu. The principle is the same as for the yield sensor, the "Multiple load" option is selected, in the field "Current moisture offset" the value of the measurement performed by the system on the combine harvester is read in the "Current moisture offset " field, and we enter the current value of the calibrated moisture meter in the "Moisture difference (%)" field below. After updating the calibration, the values are applied retroactively to both previous and subsequent measurements.

Figure 17. Moisture sensor calibration menu

4. RESEARCH RESULTS AND DISCUSSIONS

In the technical-technological process of barley harvesting, the first measurement ("Load 1B") shows from the results presented (Table No. 3) that the difference between the mass measured by the combine harvester and the mass measured by the calibrated scales is about 23%, i.e. that the device on the combine harvester weighed 743 kg less than the scales. After three measurements were entered into the calibration menu of the yield sensor, the last, fourth measurement ("Load 4B") was carried out, in which error values of 2% were obtained, i.e. the device on the combine weighed 62 kg less than the calibrated scale, which is a more accurate result than the first measurement. From the values obtained, it can be concluded that the yield sensor is sufficiently calibrated so that it can continue to work without additional measurements. As part of the same measurements, the moisture content of the threshed grain was measured using the same principle. In the first measurement ("Load 1B"), the difference was 3.5 %, which is outside the range due to the limit values for the absorption of mass into objects, so that further measurements were carried out. Three further measurements followed, with a value of 0.2% being achieved in the last measurement ("Load 4B") and no further measurements being necessary. The values achieved can be influenced by soiling of the sensors during further work, so that both sensors must be cleaned for a certain period of time as a preventive measure. The technical-technological operation of the wheat harvest was carried out according to the same principle as for barley. In the first measurement ("Load 1W"), it can be seen from the results displayed (Table No. 4) that the difference is 14.3%, i.e. the combine harvester's yield sensor measured 812 kg less than the calibrated scales used as a reference device. Three further measurements were carried out in which the difference after the last measurement ("Load 4W") was between 1-2%, more precisely 70 kg, which is a small difference compared to the initial mass, so that no additional calibration of the sensor is required after this measurement. In the moisture measurement, the sensor showed a difference of 3.7% in the first measurement ("Load 1W"), so as in the previous case, three more measurements were taken, with no difference after the last one ("Load 4W"), i.e. the value of the reference hygrometer and the "Ag Leader" moisture sensor within the yield monitoring system matched. In addition to monitoring moisture content and yield, the most important parameters during harvest, this system offers the possibility of geo-positioning the readings. All data can be analyzed and applied in production in the form of variable standards for the use of seeds, fertilizers or chemicals, using appropriate software such as QGIS, Agro-Map, Trimble Ag software and specialized technical tools. [3, 10, 12].

Table 3. Comparative presentation of the measurements of mass, threshed mass and moisture content in the barley harvest

Name and number of measurements	Mass (kg) (harvester)	Mass (kg) (measuring device)	Moisture percentage (harvester)	Moisture percentage (measuring device)
Load 1B	2467	3210	9.9%	13.4%
Load 2B	2922	3287	12.1%	13.6%
Load 3B	3334	3440	12.7%	13.1%
Load 4B	3495	3557	13.2%	13.4%

Table 4. Comparative representation of mass measurement, threshed mass and moisture content in the wheat harvest

Name and number of measurements	Mass (kg) (harvester)	Mass (kg) (measuring device)	Moisture percentage (harvester)	Moisture percentage (measuring device)
Load 1W	4882	5694	11.0%	13.7%
Load 2W	5277	5508	12.8%	13.6%
Load 3W	5496	5583	13.1%	13.5%
Load 4W	5457	5527	13.7%	13.7%

5. CONCLUSION

In this research, the calibration process of the yield monitoring and mapping system was carried out during the technological operation of harvesting barley and wheat. The research has shown that the systems are available for retrofitting harvesting machines and can perform precise measurements and displays in real time for the purpose of measuring the yield level and its mapping when properly calibrated. The results obtained, i.e. measurement errors of 2-3% when measuring yield height and moisture measurement with an even lower error percentage after the calibration process, confirm the justification for using this system. To achieve realistic results, at least 3-4 measurements are required during the calibration process, which is the recommendation of the system manufacturer and was confirmed by this study. With the geolocation of the results obtained, it is possible to analyze the entire production process and opens up the possibility of applying VRA technology. The recordings of the yield sensors can be compared with satellite images, i.e. vegetation indices of the crops, and the overlaps of the results obtained can be used in prediction maps for the following crop years of these crops. Yield monitoring and mapping is just one of the steps towards sustainable agricultural production, where we need to make rational use of resources, which are not unlimited, as a contribution to a better relationship with the environment and the production of higher quality food.

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ASH MELTING TEMPERATURES FOR BIOMASS FUELS: EFFECT OF FUEL SAMPLE PREPARATION BY ASHING AT DIFFERENT TEMPERATURES

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Abstract. In the discussion on biomass as a renewable energy source, its benefits are repeatedly recognised: - reducing greenhouse gas emissions by substituting fossil fuels; - increasing energy security by diversifying the energy mix and reducing dependence on imported fuels; - creating economic prospects by promoting rural development, job creation and valorisation of waste streams. However, the utilisation of biomass in combustion processes faces some challenges. This article emphasises one of them: the ash problem due to the pronounced tendency to form deposits on the heating surfaces. In order to properly design or select a biomass combustion system, the indicators of the tendency of biomass ash to form deposits on the heating surfaces must be adequately determined. Determining ash melting temperatures for biomass is crucial for understanding combustion behaviour and potential problems such as slagging and fouling. Biomass ash melting temperatures are typically determined at 550 °C for biofuels and 815 °C for solid mineral fuels. Some established certification schemes and national regulations favour the preparation of biomass samples by ashing at 815 °C. In this paper, the question is answered whether and how the ashing temperature of the biomass sample influences the characteristic points of the ash melting temperatures. The characteristic ash melting temperatures were determined for different types of biomass (wood chips, soybean and maize straw), where the ash sample was obtained by ashing at three different temperatures (550, 710 and 815 °C).

Keywords: wood chips, soybean straw, maize straw, indicators for slagging and fouling

1. Introduction

It is widely recognised that biomass is a significant source of renewable energy that can (at least partially) replace fossil fuels to power a green and sustainable society and accelerate the development of a circular bioeconomy. However, due to its specificity, this energy source also poses implementation challenges. Biomass, in instance, is more geographically dispersed, has a lower energy density and conversion efficiency than fossil fuels [1]. Furthermore, depending on the biomass, technology and expertise used, certain pollutants are released during the conversion process [2] that are more or less common to all fuels. The utilization of biomass therefore requires complex processes of material handling, pre-treatment and design of the processing facilities.

When designing or selecting a biomass combustion (and, more broadly, thermochemical conversion) facility, as well as optimizing combustion conditions, it is crucial to understand and predict the behavior of biomass ash. Key issues associated with biomass ash include [3, 4]:

- **Slagging:** molten high temperature ash deposits build up on the furnace walls and on the heat transfer surfaces, hindering heat transfer;
- **Fouling:** unmelted ash deposits at lower temperatures, that accumulate on the surfaces of heat exchangers and also impair heat transfer;
- Biomass ash deposits are often more difficult to remove than coal ash deposits as they have lower porosity and smoother surface, greater strength and viscosity [5];
- **Agglomeration:** formation of larger ash clusters through melting and sticking together of ash components, which can obstruct combustion ("trapping" of the fluidized bed) and the flue gas flow;
- **Alkali-induced corrosion:** chemical reactions between the alkali metals contained in the biomass ash (especially in combination with Cl or S) and the boiler materials that lead to material deterioration.

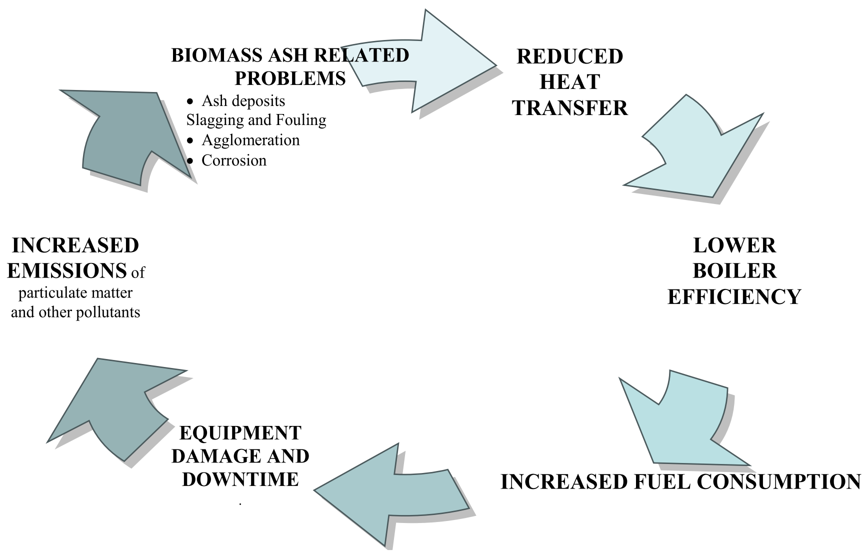

Figure1. Impact of biomass ash-related issues on biomass-based energy systems

This paper addresses these biomass ash-related issues, which have a significant impact on the reliability and efficiency of biomass-based energy systems (see fig.1). For this purpose, two types of biomass were studied, namely two agricultural (soybean and maize straw) and one woody biomass (wood chips). The proximate and ultimate analysis, as well as the chlorine content, were determined for all three biomass samples. In addition, the characteristic ash fusion temperatures (AFT) were determined in relation to the shrinkage starting temperature (SST), the deformation temperature (DT), the hemisphere temperature (HT) and the flow temperature (FT) as well as their dependence on the alkali content (K, Na) of the ash and the chlorine content of the original biomass. The biomass samples were also ashed at three different temperatures to investigate how the ashing temperature affects both the ash melting stages and the carbon, hydrogen, and sulfur content of the ash.

These findings can help industrial users of biomass gain a better understanding of how biomass characterisation, namely its ash, influences combustion optimisation and technology selection. Furthermore, the work answers the testing laboratory's question of whether different ashing temperatures change the indicators for the biomass ash deposition tendency, and if so, for which type of biomass this influence is more pronounced.

2. Methodology

The biomass samples were prepared according to the standard [6]. All samples were dried in a drying oven (Binder GmbH) at a temperature of 105 °C and then ground with a mill.

Proximate analyzes were carried out in accordance with the standards [7-10]. The ash content of all samples was determined using a muffle furnace (Vecstar furnace) at 550 °C, 710 and 815 °C according to [8]. The analysis is done in triplicate.

The LECO CHN 628 series was used to determine the total N, C and H content in solid biofuels and representative biomass ash samples according to the standard method [11], while the O content was calculated according to [12]. All measurements were carried out in triplicate.

The ash fusion temperatures (AFTs) was investigated on a Leitz Wetzlar device for determining ash melting in accordance with the standard [13]. Ash samples are obtained by controlled thermal decomposition of the fuel in a muffle furnace. In this case, as already mentioned, the ash was obtained at three different ashing temperatures. The ash thus obtained is then pressed into a cylinder. The prepared samples are then subjected to uniform heating under oxidizing or reducing conditions, and the AFTs are monitored by measuring the dimensional and shape changes of an ash cylinder as a function of temperature, identifying four characteristic temperature points, as shown in Fig. 2. In this case, the characteristic AFTs were determined in an oxidizing atmosphere, as this corresponds better to real combustion conditions and is more cost-effective. Moreover, the difference between the results obtained under oxidizing and reducing conditions is negligible for samples with low Fe content, which is generally a characteristic of biomass [14].

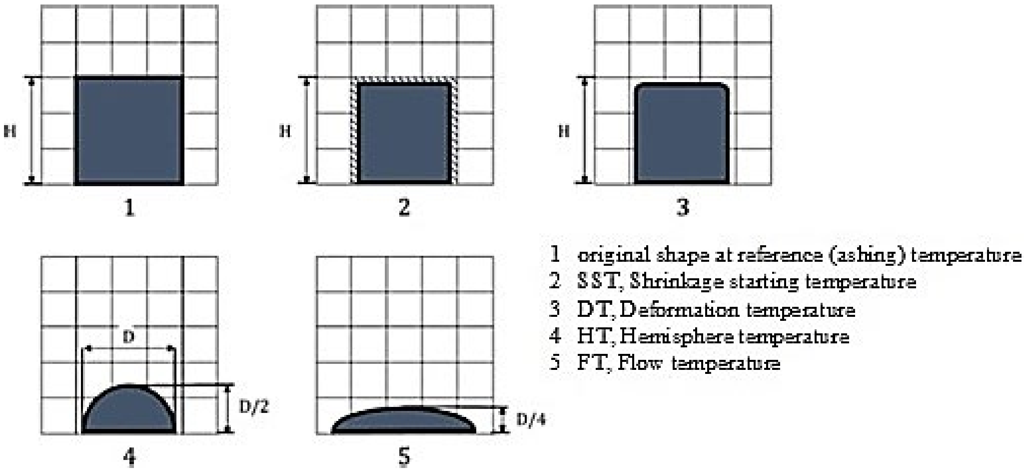

Figure 2. Visual determination of the characteristic AFTs [13]

The alkali content (Na and K) in the ash of representative biomasses was determined using a flame photometer - Sherwood Scientific Ltd. PF360, in accordance with [15]. The chlorine content in biomass samples was determined using a standard method according to [16].

3. Results and discussion

The physico-chemical composition of biomass is not uniform and varies considerably depending on the plant species, growing conditions (climate, irrigation, soil type/pH, fertilization, distance from the pollution source) and the particular plant part. The process of collecting, transporting, and storing biomass also has a significant impact on its composition. The value of a particular biomass as a fuel is best categorized by a proximate, ultimate analysis and heating value. According to the findings in Table 1, all biomass samples are highly acceptable for burning, considering the moisture content (<10%wb) and the ash concentration ranging from 1.28 to 3.38%.This is supported by the high calorific value of these biomasses. All three biomasses have a pronounced volatility and consequently a lower fixed carbon content than coal, which is a primary attribute of biomass as a fuel. This requires different combustion system designs compared to coal, the fuel most similar to biomass.

Table 1. Proximate and ultimate analysis of representative biomass

			wood chips	maize straw	soybean straw
Proximate analysis	Inherent moisture	%	8.75	9.75	9.10
	Ash 550°C	$\%_{dwb}$	1.28	3.38	2.33
	C-fix		17.49	17.72	15.17
	Volatile		81.23	78.90	81.15
Heating value	High	MJ/kg	19.59	18.05	20.87
	Low		18.36	16.78	19.57
Ultimate analysis	Total carbon	$\%_{dwb}$	49.57	46.43	47.88
	Hydrogen		5.94	6.20	6.29
	Sulfur		0.02	0.09	0.13
	Nitrogen		0.22	0.54	0.75
	Oxygen*		42.96	43.36	42.61
	Chlorine	ppm	84	1219	757
		%dwb	0.01	0.12	0.08

*Oxygen = 100% - Ash 550°C - Carbon - Hydrogen – Nitrogen; dwb - Calculated on dry weight basis

The organic compounds contained in biomass consist mainly of carbon (C), hydrogen (H), oxygen (O) and nitrogen (N) with traces of chlorine (Cl) and sulfur (S). Again, all three samples show a typical characteristic of biomass as a fuel - they have a significantly higher content of O, but a lower Cl and S content (compared to coal). While a high O is disadvantageous as it represents internal ballast, does not burn but facilitates combustion and displaces other combustible compounds, a low N, Cl and S content is beneficial for pollutant emissions.

After determining that all biomass samples were suitable for combustion, the effects of different ashing temperatures on the ash yield (Figure 3) and the characteristic ash melting temperatures (Table 2) were investigated.

As can be seen from Fig. 3, the ashing temperature has influence on the ash yield, whereby the test results indicate that the ash yield decreases with increasing ashing temperature due to the release of volatile compounds and the change in mineral composition. The effect is greatest for maize straw (ash yield decreases by 0.48 %) and lowest for wood chips (0.26 %). Furthermore, this effect is more pronounced for straw samples at lower temperatures (550-710°C), whereas for wood chips in the higher temperature window (710-815°C).

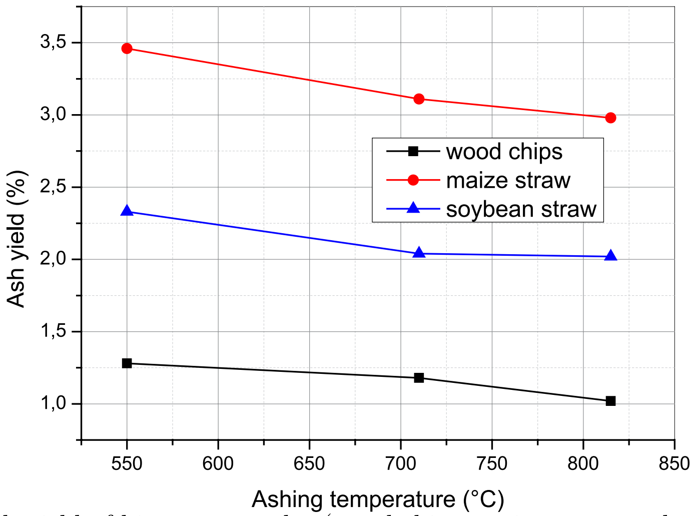

Figure 3. Ash yield of biomass samples (wood chips, maiye straw and soybean straw) at different ashing temperatures calculated on dry mass

Laboratory AFT tests estimate melting behavior of the ash and is therefore an essential indicator of the slagging and fouling tendency. In addition, higher AFTs are preferred, especially the first two characteristic temperatures, as the ash is then less sticky and less prone to forming deposits.

Table 2. The characteristic ash melting temperatures at different ashing temperatures of representative biomass samples

temperature [°C]	wood chips			maize straw			soybean straw		
	550	710	815	550	710	815	550	710	815
SST	1089	1125	1200	1015	1050	1085	1160	1170	1200
DT	1154	1230	1280	1075	1090	1095	1260	1290	1300
HT	1420	1345*	1360*	1190	1160	1170	>1400	>1400	>1400
FT	1425	1350	1365	1220	1190	1200	>1400	>1400	>1400

* The HT of these samples could not be evaluated due to the instantaneous deformation of the sample, so a difference of 5°C is assumed for the calculation of the indicator, as was the case for the sample obtained at an ashing temperature of 550°C.

The results presented in Table 2 show that SST and DT increase with increasing ashing temperature for all biomass ash samples. However, the values of HT and FT for the ash of wood chips and maize straw are higher for the ash obtained at an ashing temperature of 550 °C than for the ash obtained at higher temperatures. At the same time, HT and FT for all ashes obtained at 710°C and 815°C increase with the ashing temperature. Soybean straw has the best properties in terms of high all AFT points.

In an attempt to explain the differences in the characteristic AFTs of the ash obtained at different ashing temperatures, a partial elemental analysis of the ash was performed, focusing on the determination of the residual combustible matter and the content of alkali metals as the elements most influential for the behavior of the ash during combustion.

An elemental analysis of the ash was carried out to determine if unburned hydrogen, carbon and sulfur were present in the ash samples of representative biomass obtained at different ashing temperatures (Figure 4). Although the ashing method using a muffle furnace at 550°C, 710°C and 815 °C is used as standard to prepare ash samples for characterization [8], the results from Fig. 4 show that unburned C and H are still present in the samples prepared in this way.

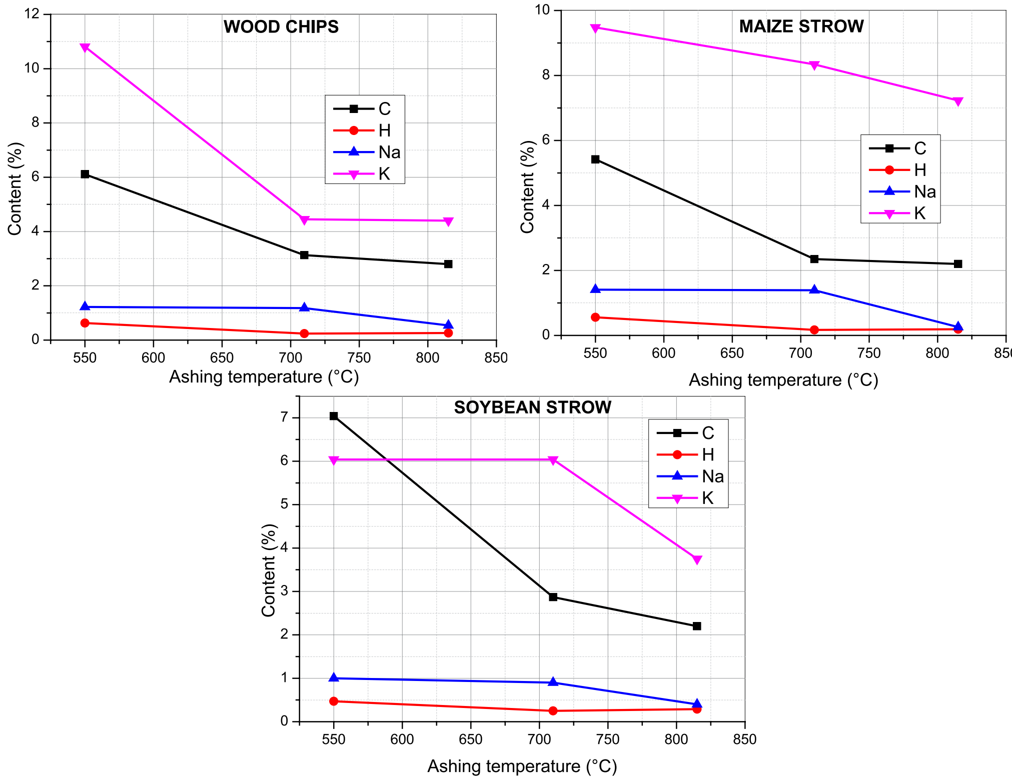

Figure 4. H, C, S, Na and K content in ash samples obtained at different ashing temperatures

The elemental analysis revealed no nitrogen or sulfur content in any of the ash samples. The C and H content in biomass ash is significantly affected by the ashing temperature, with higher temperatures resulting in lower content. As the ashing temperature increases, residual organic matter burns more completely, leading to a decrease in total carbon and hydrogen in the ash. In all biomass ash samples, this effect is more pronounced at temperatures of 550-710°C.

The ashing temperature has an obvious influence on the alkali content in the ash samples (see Fig. 4) and consequently on the AFT, with higher temperatures often leading to increased volatilization of alkali metals and potential changes in ash slagging/fouling tendencies. Potassium reduction is more pronounced in wood chips and maize straw at 550°C -710°C, whereas it is more pronounced in soybean straw in the temperature window 710°C -815°C. Sodium, which is significantly lower than potassium, decreases more intensively in the temperature interval 710°C -815°C (Fig. 4). Analysis of the diagram in Figure 4 and the AFT values in Table 2 clearly shows that a higher alkali content, especially potassium, leads to lower ash melting temperatures, which are in accordance with the trends observed by [14, 17].

4. Indicators for the ash tendency to form deposits on the heating surfaces

In addition to the AFT test, a number of indicators have been developed to assess the tendency of ash to form deposits. Some of them, which are consistent with the analyzes presented in this paper, are listed in Tab. 3, and the values of the indicators for the representative biomass ashes are shown in Tab. 4.

Table 3. The calculations and ranges for indicators of the ash tendency to form deposits on the firing side of heating surfaces

Indicator	Calculation	Range	Tendency to form deposits	Reference
Cl [%]	-	<0.2	low	[18]
		0.2-0.3	medium	
		0.3-0.5	high	
		>0.5	extremely high	
TA, total alkalis [%]	Na_2O+K_2O	<0.3	low	[19]
		0.3-0.4	medium	
		>0.4	high	
AFI, Ash fusibility index [°C]	(4 SST +HT)/5	>1342	low	[18]
		1232-1342	medium	
		1052-1232	high	
		<1052	extremely high	
DT [°C]	tab.3	>1100	low	[18]
		900 -1100	medium	
		<900	high	

Table 4. Indicator values for selected biomass ash samples

			Na_2O %	K_2O %	SST °C	HT °C	Cl %	TA %	AFI °C	DT °C
wood chips	550	°C	1.64	12.98	1089	1420	0.01	14.62	1155.2	1154
	710		1.59	5.35	1125	1345	0.01	6.94	1169	1230
	815		0.73	5.29	1200	1360	0.01	6.02	1232	1280
maize straw	550	°C	1.90	11.39	1015	1190	0.12	13.29	1050	1075
	710		1.88	10.2	1050	1160	0.12	12.08	1072	1090
	815		0.35	8.69	1085	1170	0.12	9.04	1102	1095
soybean straw	550	°C	1.35	7.26	1160	1400	0.08	8.61	1208	1260
	710		1.21	7.26	1170	1400	0.08	8.47	1216	1290
	815		0.54	4.47	1200	1400	0.08	5.01	1240	1300

From the results of Table 4, it can be concluded that the chlorine content shows the lowest tendency and the DT test the mildest tendency for the biomass samples analyzed. Depending on the DT, the ashes show either a low (wood chips and soybean straw) or a medium tendency (maize straw), while the total alkali shows the most extreme - high potential for the formation of deposits for all biomass ashes analyzed. The AFI indicator is particularly remarkable. It has been empirically developed to favor the initial temperature of deformation, i.e. the shrinkage starting temperature (SST), while taking into account HT as the initial temperature of extensive ash melting. The AFI shows that ashes obtained at higher ashing temperatures are less prone to deposit formation.

5. Conclusion

The ash fusion temperatures observed in the laboratory are commonly used to assess the tendency of fuels to form ash deposits. Although laboratory conditions do not always perfectly reflect conditions in industrial boilers, experimental AFTs are still a preferred tool for predicting potential slagging and fouling problems in real combustion applications. This study investigates whether varying the ashing temperature during sample preparation has an influence on the measured AFT values and, consequently, the prediction of ash deposition tendencies on heating surfaces. Based on the tests carried out, the following conclusions were drawn:

- Ashing temperature affects AFTs. SST and DT increase with increasing ashing temperature for all biomass ash samples. The HT and FT values for the ash of wood chips and maize straw are higher for the ash obtained at an ashing temperature of 550 °C than for the ash obtained at higher temperatures. At the same time, HT and FT for all ashes obtained at 710°C and 815°C increase with the ashing temperature.

- The ashing temperature has a significant influence on the ash yield –
- the ash yield decreases as the ashing temperature increases.
- The ashing temperature has an influence on the alkali content in the all ash samples – the alkali content decreases as the ashing temperature increases.
- As the ashing temperature increases, residual combustible matter burns more completely, leading to a decrease in the total carbon and hydrogen content in the ash. For all biomass ash samples, this effect is more pronounced at ashing temperatures of 550 and 710°C.
- Of the indicators used, the indicator based on the Cl content of the biomass is the mildest and all ashes show a low tendency to form deposits according to it. The situation is similar with DT, which shows only a medium tendency to deposit for maize straw ashes, while the others show a low tendency. The strongest is TA, where all ashes show a high tendency to deposit. The AFI indicator provides perhaps the most realistic prediction. Ashes obtained at ashing temperatures of less than 815 °C are more likely to form deposits.
- Of all biomass ash samples examined, maize straw ash showed the greatest tendency to form deposits.
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The composition of the biomass ash, like the composition of the biomass, varies greatly and is determined by a variety of causes. Therefore, the results refer exclusively to the biomass samples examined in this work.

Acknowledgments

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ANALYSIS OF ACCIDENTS INVOLVING AGRICULTURAL TRACTORS IN PUBLIC TRANSPORT IN THE REPUBLIC OF SERBIA FOR THE PERIOD 2014-2024

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Abstract. Tractors are among the main causes of numerous accidents in public transport, as well as in agricultural production, forestry, and construction.

Between 2014 and 2024, a total of 150,794 accidents occurred in public transport in the Republic of Serbia, resulting in 214,285 injuries and 5,986 fatalities—an average of 544 deaths per year.

During the analyzed period, tractors were involved in 4,400 road accidents, including 418 fatal ones, which corresponds to an average of 29 deaths per year. Tractor-related accidents also caused 1912 serious and minor injuries, averaging 174 annually.

When examined by month, tractor accidents in public transport most frequently occurred in September, while Saturdays were identified as the most accident-prone day of the week.

In 2014, tractors were involved in 620 road accidents, including 37 fatal ones. By 2024, the number of tractor-related accidents had significantly decreased to 418, with 19 fatalities.

The main causes of accidents involving tractors in public transport in the Republic of Serbia include:

- Non-compliance with the Law on Public Transport,
- Insufficient and discontinuous training of tractor operators,
- Improper technical and operational use of tractors, and
- Alcohol abuse.

Overall, the safety of tractor use in public transport in the Republic of Serbia remains unsatisfactory.

Keywords: Republic of Serbia, tractors, accidents, public transport, education

1. Introduction

According to data from the agricultural census of the Republic of Serbia [1], [15], which were published at the end of 2023, the Republic of Serbia has 482,498 tractors of all categories for carrying out work on 4,073,703 hectares of available agricultural land, of which 3,275,100 hectares or 80.39% are actively used. Also, according to data from the 2023 agricultural census, 1,150,653 inhabitants of the Republic of Serbia are engaged in agricultural production, which represents 17.4% of the total population.

Of the mentioned total number of tractors (482,498), only 40% are registered, which should mean that they meet the basic technical requirements for participation in public transport. About 350,000 tractors are older than 20 years.

There are also about 2.5 million attached machines and tools in use, of which over 90% are older than 10 years.

From the aforementioned data, it is easy to conclude that the tractor as the basic driving unit in agriculture, either in a unit with attached machines or implements, or as an independent motor vehicle, has a very high-risk factor of causing accidents and thus frequent forms of injury to participants when used in public transport in Serbia.

According to the literature [6], [9], [10], [11] and the data of the Traffic Safety Agency of the Republic of Serbia [2], tractor drivers, today, on different categories of roads in the public traffic of the Republic of Serbia, participate with a high share in causing traffic accidents with different and dangerous consequences.

Tractors have a significant application in agricultural and other works (construction and forestry works) and transport, when moving on different types of surfaces and categories of public roads. In such numerous and different circumstances, tractors are potentially dangerous traction machines, especially if they are not used according to certain rules of safety, prevention, protection and legal regulations.

Data from the literature show [2] that accidents and injuries with tractors most often occur in the spring, when the volume of work in agriculture is increased. Injuries are very diverse, severe and affect all parts of the operator's body, with the appearance of a high degree of disability [6], [9], with mostly large material damages, because the machines are very expensive. Unfortunately, very often there are tragic consequences for drivers and other road users.

The tendency of the annual increase of these machines is from 5,000 to 20,000 pieces due to the increased volume of agricultural works. In addition to this number of tractors, the Republic of Serbia has over 400,000 other types of working machines and more than 30,000 combines [1]. So, the approximate total number of mobile agricultural machines with their own engine and the possibility of participating in public transport in the Republic of Serbia, today exceeds the number of 1,000,000 pieces.

With such a large number of moving machines, there is a high risk of an annual increase in the occurrence of accidents in public transport or in the processes of agricultural production.

At the same time, research [8], [10] should also be noted, which show that the financial effect of the events is of particular importance, since modern tractors as traction-drive and transport units are also designed for movement on public roads, and can reach purchase prices of up to 150,000 EUR or even more (tracked tractors, etc.). The prices of other self-propelled agricultural machines (harvesters) can reach over 200,000 EUR.

Aaccidents often result in considerable damage to agricultural machinery, which is when additional problems arise for the relevant institutions.

Serbia is not the only country that has serious problems with accidents related to agricultural machinery, primarily tractors. In the world, many researchers [3], [8], [12], [13] consider the tractor as one of the main causes of accidents. Regardless of the development of certain countries in the world in economic, social, technical or any other sense, the obligatory companion of intensive agricultural production and the use of modern agricultural mechanization are accidents that occur as a result of the error of the operator or the state of the machine itself. One example [14], is the agricultural production of the United States of America. there are 2.2 million workers in American agriculture, which represents 1.4% of the total number of workers in the economy. On average, around 500 accidents with tragic consequences and 120,000 accidents with serious bodily injuries occur in agricultural production. This shows that accidents in agriculture in terms of the number of victims are higher than in other economic branches that are also considered risky (construction, transport), and only in mining is the number of accidents with tragic consequences higher. That is why agriculture in America is an industry with a high risk of workplace injuries. A large number of accidents are precisely those involving agricultural machinery, primarily tractors, and then other mobile agricultural machines. Research conducted on the Australian continent [7], [13], shows that tractor accidents account for as much as 72% of the total number of accidents in agriculture. Of the total number of accidents with tractors, 61% are accidents with tractor overturning. The statistical analysis of the collected data in the three-year period of the research shows that there is no statistically significant decrease in accidents with tractor overturning, while other types of accidents with tractors show a significant increase. Analysis shows that tractors are the most common cause of agricultural fatalities in Australia. A report from Western Australia [7], for the period 2014 to 2024 found that tractors were the most common cause of agricultural fatalities, with 12 deaths per year.

In contemporary global practice, considerable attention is devoted to safety [3], [12], [13], security, and the enhancement of the technical culture of farmers, particularly operators of all working machines that may also participate in public traffic.

This is primarily achieved through educational activities and the organization of various training programs.

Ergonomics also contributes significantly to improving the level of safety in this field. The integrated signaling devices installed in tractor cabins [4], [6] through both audio and visual signals serve to inform and warn the operator of potential hazards that may arise during the work process, thereby preventing possible injuries and other accidents with potentially tragic consequences.

2. Material and Methods

Accidents Involving Tractors in public traffic in the Republic of Serbia during the period 2014–2024 were analyzed within the scope of transport activities of tractors and attached machinery during their movement/operation in public traffic on various categories of roads in the Republic of Serbia.

Data on the number of accidents [2], [15] involving tractors in public traffic were collected from the Traffic Police Directorate and the Road Traffic Safety Agency of the Republic of Serbia.

The data presented in this paper are shown in tabular and graphical form and analyzed by year and by the consequences of the accidents for the period from 2014 to 2024.

3. Research Results

Tractors have significant application in agricultural operations and transport when operating on agricultural land of various characteristics (soil with different topographical features, uncategorized roads, etc.) as well as on various categories of public roads. In these situations, they represent a potentially hazardous machine, especially if they are not used in accordance with established safety, preventive, and protective regulations.

In the literature [7], [9], [14], the human operator and the tractor are most frequently cited as constant causes of numerous accidents in agriculture, forestry, and construction, where the most common causes include: improper handling (driving tractors with inadequate technique or at inappropriate speeds in traffic, on slopes, or on lateral inclines, leading to rollovers), and maintenance-related causes (various repairs or interventions on individual components, tire replacement, refueling, adding coolant, etc.).

According to literature sources [6], [9], in the period from 1999 to 2009, in public traffic in the Republic of Serbia, an average of 469 persons were injured annually in tractor-related accidents, while an average of 62 tractor operators were fatally injured each year.

It was also determined that 144 tractor drivers were severely injured (resulting in permanent disability) annually. It should be particularly emphasized that the material damage resulting from these accidents is enormous.

Figure 1. Accidents Involving Tractors and Fatal Consequences.

The most common causes of accidents in agricultural production and public traffic [6], [9], involving tractors and other self-propelled agricultural machines are:

- carelessness of the machine operator,
- insufficient level of training for operation,
- non-compliance with traffic regulations,
- lack of knowledge of safety measures, and
- the use of technically outdated or defective machines.

Table 1. Consequences of traffic accidents involving tractor drivers in the period from 2014 to 2024.

Year	Number of accidents - public transport	Number of injured persons - public transport	Number of tragically injured persons - public transport	Number of injured persons - tractors	Number of tragically injured persons - tractors
2014	13068	18025	536	162	37
2015	13656	19350	599	187	33
2016	14409	20655	607	195	40
2017	14809	21631	579	177	29
2018	14236	20845	548	195	27
2019	14244	20418	534	164	28
2020	12311	17259	492	189	26
2021	13786	19965	521	156	24
2022	13269	19119	553	194	33
2023	13463	19059	503	143	26
2024	13543	17959	514	150	19
Ukupno	150794	214285	5986	1912	322
Prosek	12477	17848	544	174	29
%		100*	100**	0,97%*	5,4%**

* in relation to the total number of injured

** in relation to the total number of casualties

In the territory of the Republic of Serbia, according to research, during the period from 2014 to 2024, tractor drivers were frequently involved in direct traffic accidents in public traffic (injured persons). The data on the number of persons injured in traffic accidents (Table 1), which were caused by tractor drivers or in which they were direct participants, for the period 2014–2024, indicate a serious aspect of accidents caused by the interaction between humans and tractors.

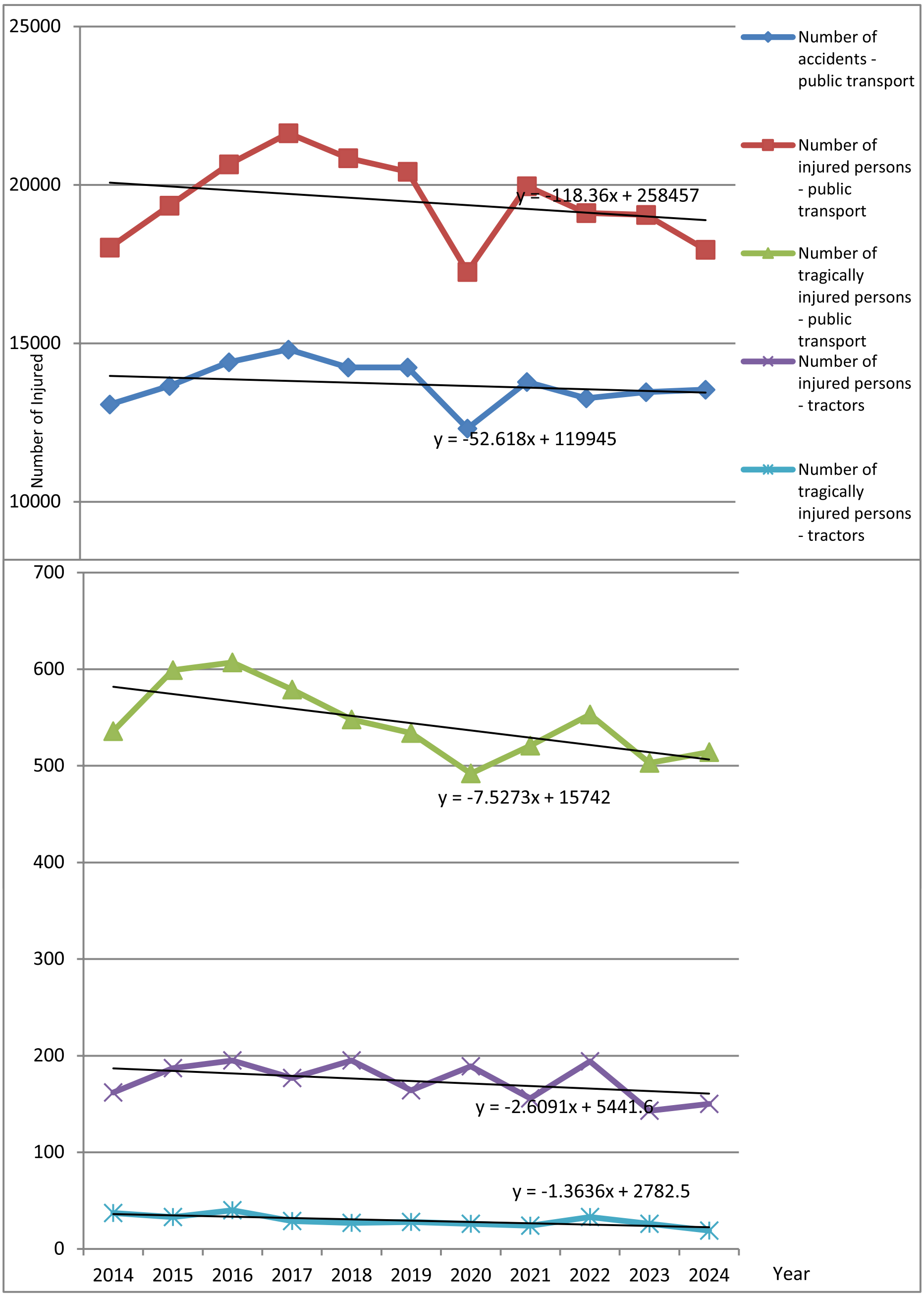

Figure 2. Graphical representation and trend of the consequences of traffic accidents involving tractor drivers for the period 2014–2024.

By analyzing the presented data (Table 1, Fig. 2), concerning results are observed regarding the number of casualties.

In public traffic in the Republic of Serbia in the research period from 2014 to 2024, out of the recorded 150,794 traffic accidents, a total of 5,986 persons were fatally injured and 214,285 persons were slightly or severely injured. In accidents caused by or involving tractor operators and other agricultural machinery, a total of 1,912 persons were slightly or severely injured, which represents 0.97% of the total number of the injured, while 322 persons were fatally injured, or 5.4% of the total number of fatal casualties.

In particular, the analysis of accidents involving tractors shows positive changes in the direction of reducing the number of such incidents. The number of injured persons decreased from 162 to 150 during the analyzed period, with an average decline of about one person per year. The number of fatalities in these accidents shows the most significant reduction across the dataset — from 37 deaths in 2014 to 19 deaths in 2024.

The collected data indicate that for all categories of consequences, the trend is declining. Although the data show improvement from year to year, the number of fatal casualties remains concerning, with an average of 29 deaths per year during the study period. Based on the presented data, it can be concluded that the number of casualties in accidents involving tractors has slightly decreased in the period from 2014 to 2024.

In general, the data indicate that the total number of traffic accidents is not decreasing, but the number of the most severe outcomes is decreasing. The reason for this reduction is not solely attributable to human factors, but is largely a consequence of improvements in active and passive vehicle safety, better medical care, increased supervision, and preventive campaigns. The particularly noticeable decline in the number of fatalities in tractor-related accidents may indicate strengthened regulation, mandatory technical inspections, and an increased awareness of safety in rural agricultural communities.

Analysis of the collected data also shows that, when observing days of the week, the highest number of accidents occurs on Saturdays. Regarding months of the year, April is the most critical, which corresponds to the start of the agricultural work season.

Despite all of the above, work with tractors and other agricultural machinery still results in serious and tragic consequences, most often because operators do not perform their tasks in accordance with the existing regulations and safety rules, which are not consistently followed.

Review and analysis of literature [6], [9], [10], [11], as well as research results in the Republic of Serbia, indicate that accidents involving tractors and other mobile agricultural machines continue to occur, despite numerous preventive measures and legal regulations.

Figure 3. Faulty and improper tractor units in public traffic in the Republic of Serbia.

This is primarily the result of carelessness, unskilled handling, machinery malfunction (Figure 3), insufficient education and lack of discipline (e.g., factors such as the unauthorized consumption of alcohol during work and transport activities), and the psycho-physical fatigue of tractor and agricultural machinery operators.

The authors of this study believe that accidents also occur due to the lack of continuous professional training and accompanying courses for the proper use and maintenance of tractors and machinery. Such training must be organized and implemented through a continuous, coordinated, and serious effort by all relevant stakeholders, primarily societal institutions (Ministry of Agriculture, Ministry of Infrastructure and Transport, Ministry of Internal Affairs, educational institutions, associations of agricultural producers, and other relevant organizations and individuals).

4. Conclusion

Analyses show that traffic accidents involving tractors and other agricultural machinery in public traffic in the Republic of Serbia during the period 2014–2024 exhibit the following main characteristics:

- The average annual number of fatalities in accidents is 544.
- The average number of tractor drivers or participants who died is 29.
- The average number of participants sustaining minor or serious injuries in accidents involving tractors is 174.
- Collected data indicate a downward trend across all categories of consequences. Although the situation shows gradual improvement year by year, the number of fatalities an average of 29 per year during the study period remains concerning.

Accidents involving tractors and agricultural machinery are currently a common occurrence in Serbia, mainly due to insufficient ongoing training and specialized courses for the proper use and maintenance of these machines. There are also significant gaps in knowledge and compliance with basic traffic regulations among tractor operators, as well as irresponsibility and lack of discipline during the use of tractors and other mobile agricultural machinery.

Future research and preventive actions should focus on mandatory operator training and raising technical awareness among operators, alongside enhancing tractor safety through legislative measures requiring the installation of cabins or protective frames and seat belts on all tractors used in Serbian agriculture.

The imperative for the coming period is to reduce the number of accidents involving tractors and agricultural machinery to the lowest possible level. This primarily requires ensuring that agricultural production processes are carried out in full compliance with all prescribed safety measures and labor regulations, and especially the Road Traffic Safety Law [5], when these machines are involved in transportation on public roads.

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OVERVIEW OF THE CURRENT VALUES OF THE EUROPEAN AGRICULTURAL MACHINERY DEALERS' SATISFACTION INDEX

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Abstract. The results of the CLIMMAR 2024 DSI survey reflect the improvement of manufacturer-dealer relations and the strengthening of cooperation, as the tractor dealer satisfaction index (DSI) reached its highest value ever. The recent moderate market demand for power machinery in Europe, stagnating sales and increasing competition in the market have forced tractor manufacturers to increase their support to their sales channels in the commercial, marketing and technical fields, and to improve their service levels, which is welcomed and positively assessed by dealers.

The average value of the dealer satisfaction index for the leading tractor brands, which has remained stable in recent years, started to rise in 2024. The last time we saw such an intense positive shift was in 2019, under more balanced machine market conditions.

The ranking of the tractor brands by index value showed some slight and some major movements. There was a change in the top ranking and a significant shift in the middle ranking.

Key words: Dealer Satisfaction Index, agricultural machinery distributors, agricultural machinery manufacturers, trends, CLIMMAR

1. Introduction

CLIMMAR, the European Agricultural Machinery Dealers Association, has been conducting a survey of machinery dealers in several European countries since 2011. The aim of the Manufacturer-Distributor Relationship Satisfaction Index is to provide dealers with a tool to express their level of satisfaction with the manufacturer's activities and services. (CLIMMAR 2017) (**Magó** 2015) The National Association of Agricultural Equipment and Machinery Distributors (MEGFOSZ) is a member of CLIMMAR in Hungary and an active contributor to the CLIMMAR Statistical Committee. As a result, from 2018 onwards, Hungarian machinery dealers provide data to help put the Dealer Satisfaction Index (DSI) on a more reliable basis and to provide more comprehensive data. (CLIMMAR 2018) (Magó 2019)

2. Method

In 2024, the determination of the DSI now covers eleven countries (England, Belgium, Denmark, France, Germany, Hungary, Italy, Luxembourg, the Netherlands, Poland, Sweden, and the UK).

The questionnaire itself consists of 15 chapters and 73 questions. Two new groups of questions have been added to this year's survey. The questionnaire also included an evaluation of other self-propelled machines in terms of brand image and marketing. In contrast, the chapter on anti-theft protection has been removed from the survey, as there is no significant difference between manufacturers' actions in this area.

The survey, which was carried out between 2 April and 31 May 2024, resulted in more than 800 completed questionnaires for the top ten tractor brands being received by CLIMMAR's member organisation that processes the data. The composition of the top rated brands has not changed this year. The published results of the survey present the top ten tractor brands with the highest scores, namely Case IH, Claas, Deutz, Fendt, John Deere, Kubota, Massey-Ferguson, New Holland, Same, Valtra.

For tractors, the evaluation covered several areas: brand image or awareness; brand-related marketing; marketing of spare parts, i.e. brand protection against aftermarket parts; quality of IT services; warranty and warranty-related services; and brand awareness. the manufacturer's attitude towards warranty and after-sales service; advertising and product support, i.e. the extent of the manufacturer's contribution to distributors' advertising costs; payment terms and administration; the quality of the training programmes organised by the manufacturer and their price/value ratio; management, i.e. the reality of the manufacturer's strategy and its communication; the quality of the manufacturer-dealer relationship; the contribution to profitability, the suppliers' willingness to help correct weaknesses; assistance in financial financing. (CLIMMAR 2019, 2024) (Magó 2025a)

3. Results

3.1. Dealer satisfaction index values for 2024

After evaluating the responses, CLIMMAR ranks the brands according to the overall satisfaction index of the dealers.

In the overall dealer satisfaction index for 2024 Deutz came out on top, ahead of Fendt, which has held the throne for the past five years. Claas retained its position, while Valtra made a significant "leap" onto the podium. John Deere slipped to fifth place. It is followed by Same, which is holding on to its position strongly, in sixth place. New Holland is seventh and Kubota eighth. Both have improved two or three positions on last year. Case IH and Massey Ferguson are next, down four and three places respectively from last year. **(Figure 1., 2.) (Fradier 2024)**

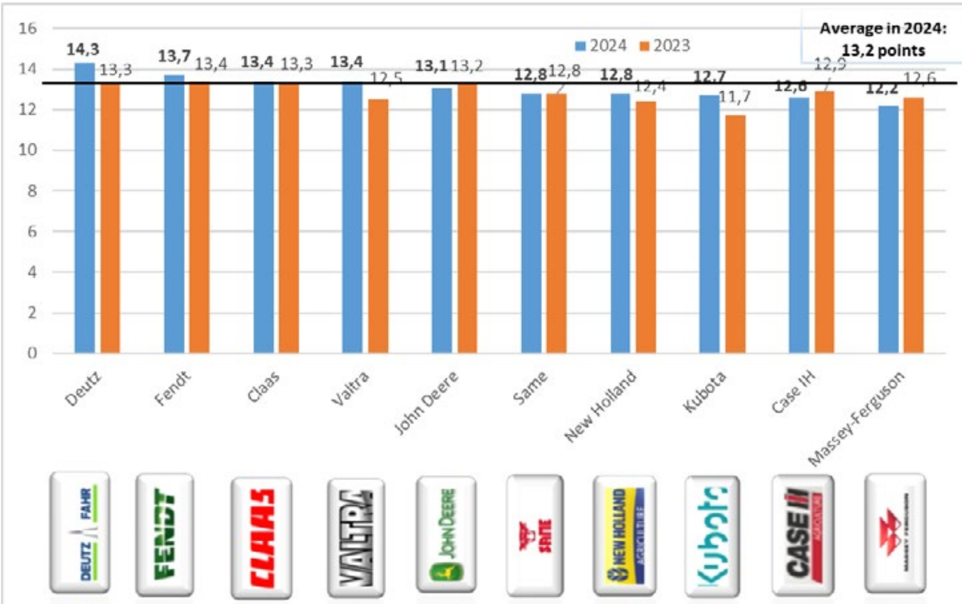

Fig. 1 Dealers' satisfaction index for each brand (own editing, Source: **Fradier** 2024, CLIMMAR)

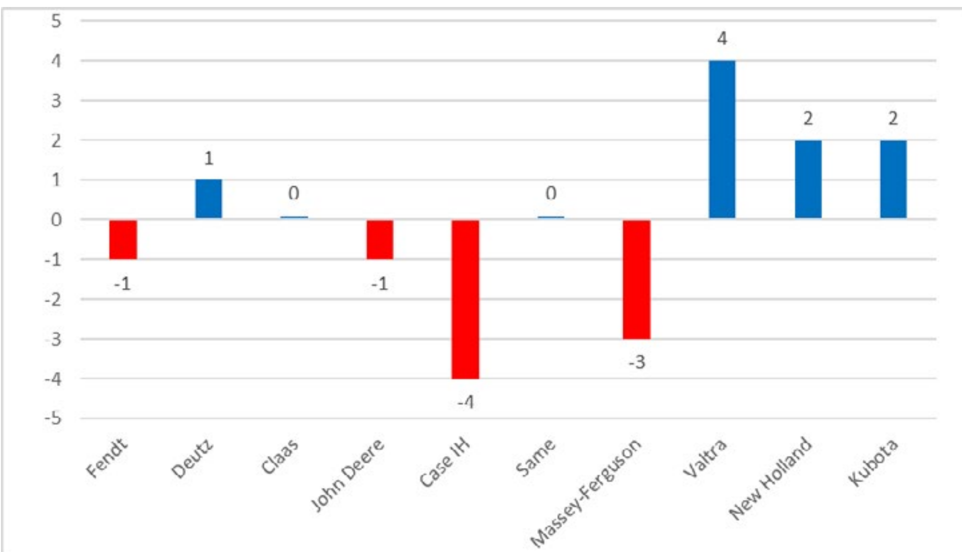

Fig. 2 Change in ranking of tractor brands between 2023 and 2024 (Source: **Fradier** 2024, CLIMMAR)

Based on the scores achieved, we can divide each tractor brand into four groups. The leader Deutz has moved away significantly by about 0.7 points from the following podium finisher Fendt and by a whole point from Claas and Valtra. The midfield is represented by John Deere, Same, New Holland, Kubota and Case IH with an index point range of 12.6 to 13.1. This is followed by Massey Ferguson in 10th place with 12.2 points, 0.4 points behind.

Looking at the change in the overall scores of each tractor brand over the past year, the most significant, almost outstanding improvements were achieved by Deutz, Valtra and Kubota, putting Deutz at the top, Valtra on the podium and Same in the middle. Fendt, New Holland and Claas made smaller improvements. John Deere's rating deteriorated slightly. Massey Ferguson and Case IH have weakened significantly over the past year (**Figure 3**).

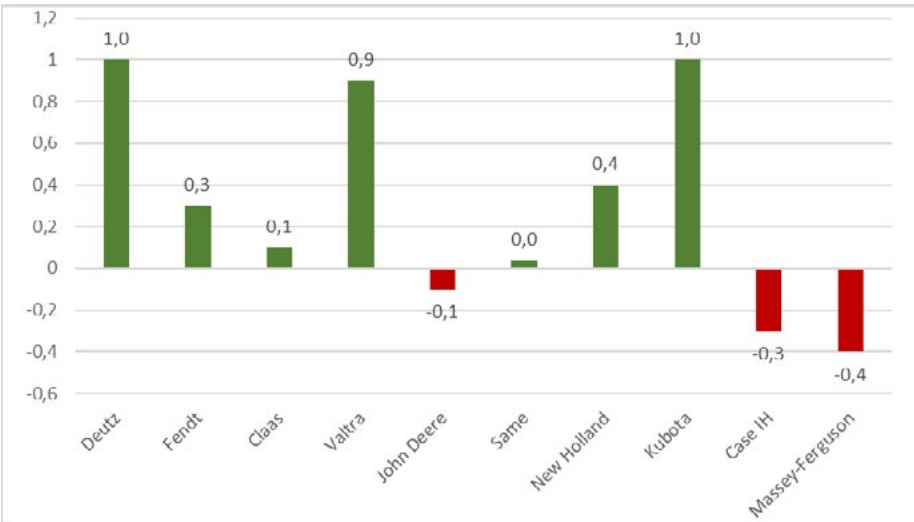

Fig. 3 Change in the aggregate rating score of tractor brands between 2023 and 2024 (Source: Fradier 2024, CLIMMAR)

In terms of the scores obtained, out of a maximum of 20 points, Deutz has 14,3 points, representing a rating of around 71,5 %, and Massey Ferguson 12,2 points, representing a rating of 61 %. The difference between the leading and the last brand is 2.1 points, an increase of 0.4 points compared to last year.

If we look at the change in the indicators for each brand from the start of the survey in 2011, it is clear that Same has made the most significant improvement, increasing its initial score by around 3.1 points. Deutz (2.8 points), New Holland and Kubota also showed an improvement, although the latter's increase was more modest, 0.7 and 0.1 points respectively. Case IH's score is the same as at the beginning. Claas, John Deere and Valtra have seen their scores fall slightly over the years (by 0.1 and 0.2 points respectively), while Fendt and Massey Ferguson have suffered a marked change in their scores, which have fallen by 1.1 points (**Figure 4**). (**Hajdú - Magó** 2021) (**Magó** 2025b) (**Fradier** 2024)

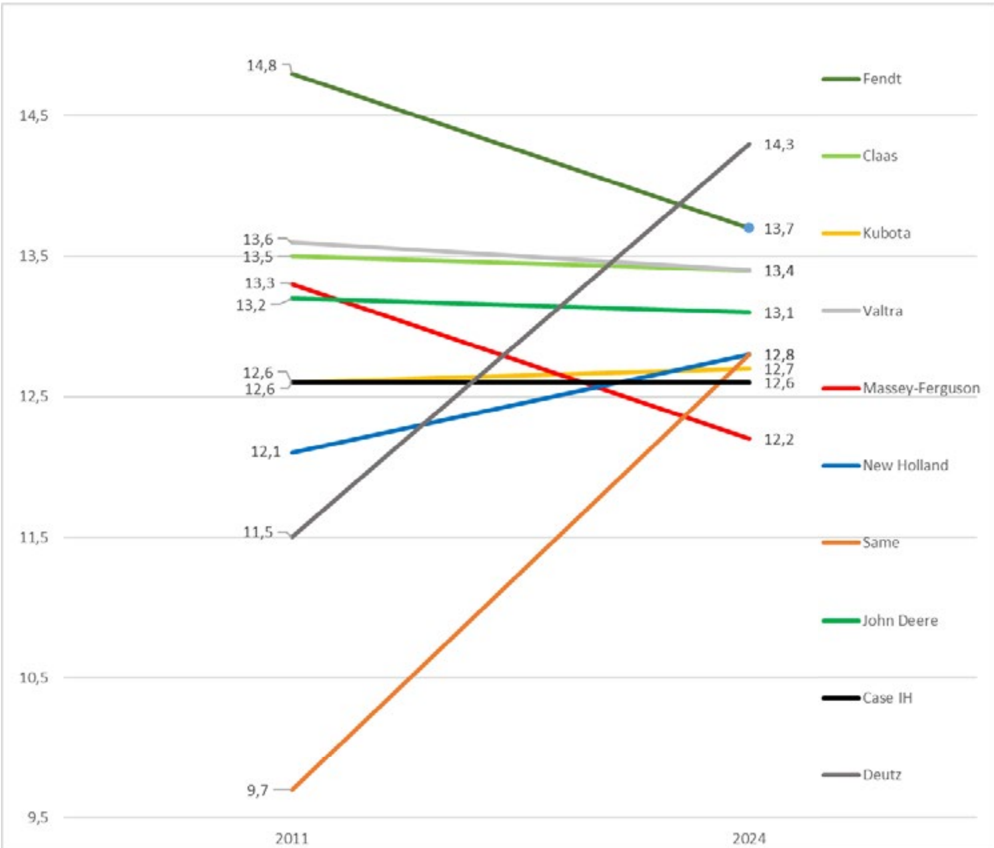

Fig. 4 Change in the aggregate rating score of tractor brands between 2011 and 2024 (own editing, Source: Hajdú - Magó 2021, Fradier 2024, CLIMMAR)

Table 1 shows the values and trends of the 2023 and 2024 DSIs by question group, disaggregated by assessment criteria. It can be clearly seen that in most areas the quality of manufacturer service has been on an upward trend in the last year. The exceptions to this are brand image, manufacturer training, contribution to profitability and improvements. (Fradier 2024)

Table 1 Average value for each group of questions in 2023 and 2024 and the trend of year-on-year change (own editing, Source: Fradier 2024, CLIMMAR)

Question groups	Average in 2023 (points)	Average in 2024 (points)	trend
brand image	14,9	14,6	↘
marketing	11,1	12,3	↗
marketing of spare parts	13,5	13,8	↗
warranty, after-sales service	13,6	13,9	↗
advertising and product support	11,5	12,4	↗
payment terms and administration	13,5	13,9	↗
manufacturer training	13,7	13,3	↘
management	13,4	13,7	↗
manufacturer-dealer relations	13,7	13,7	→
contribution to profitability	13	12,7	↘
improvements	12,4	12,3	↘
financing offers	10,8	10,8	→

3.1.1. Assistance in financing offers

The tractor brand rankings within each of the evaluation criteria can be seen to be substantially different from those found for the overall satisfaction index.

If we consider the dealer satisfaction index scores for each brand in relation to the assistance provided by the manufacturers in the financial financing, we can conclude that Deutz performed best, followed by Valtra. Fendt is third in the ranking, and the other tractor brands follow each other in a steadily decreasing order (**Figure 5**).

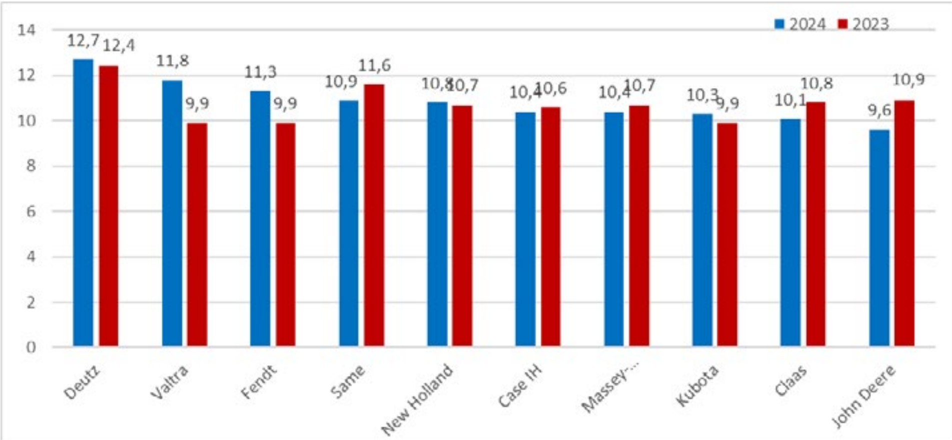

Fig. 5 Satisfaction index of dealers for each manufacturer based on assistance in financing offers (own editing, Source: Fradier 2024, CLIMMAR)

In terms of financing, the ratings of Valtra and Fendt hves improved significantly, while Kubota's rating has improved slightly over the past year. This is a significant shift compared to the previous year, when all the tractor brands surveyed were downgraded in 2023. This year, John Deere's rating deteriorated the most, followed by Same and Claas, and to a lesser extent Massey Ferguson and Case IH (**Figure 6.**).

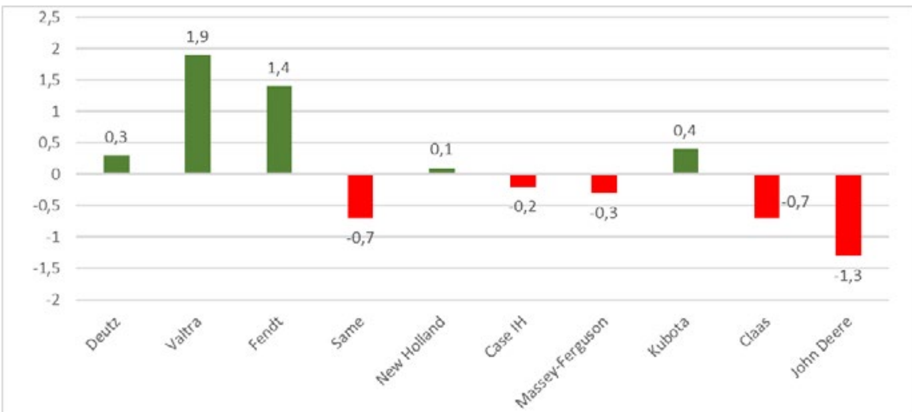

Fig. 6 Change in dealers' satisfaction index from 2023 to 2024 for each manufacturer, based on the assistance provided in the financing offers (own editing, Source: **Fradier** 2024, CLIMMAR)

3.1.2. Manufacturer-dealer relationship

The other priority area is the quality of the manufacturer-dealer relationship (**Figure 7**). Compared to the previous year, the quality of Kubota and Deutz has improved the most. They are followed by Fendt, then Valtra, and New Holland. Massey Ferguson's rating remained unchanged in this respect. Claas and Case IH have seen the biggest declines, but Same and John Deere have also lost ratings (**Figure 8**).

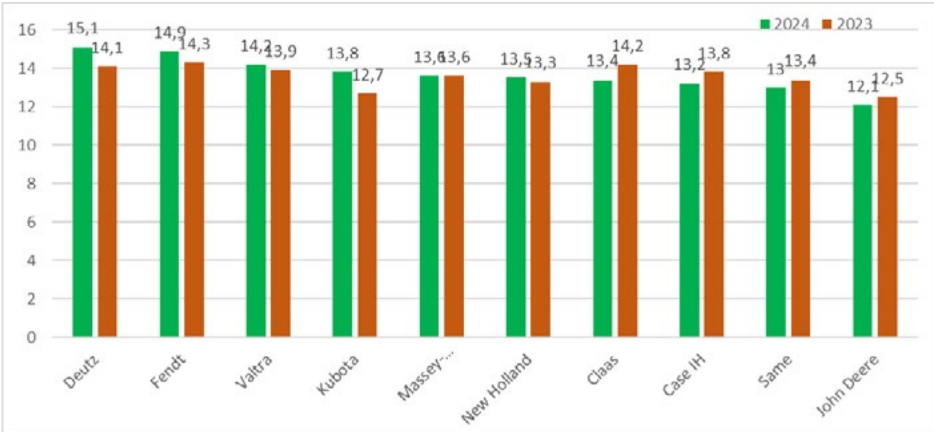

Fig. 7 Machinery dealers' satisfaction index for each manufacturer, based on the quality of the manufacturer-dealer relationship (own editing, Source: **Fradier** 2024, CLIMMAR)

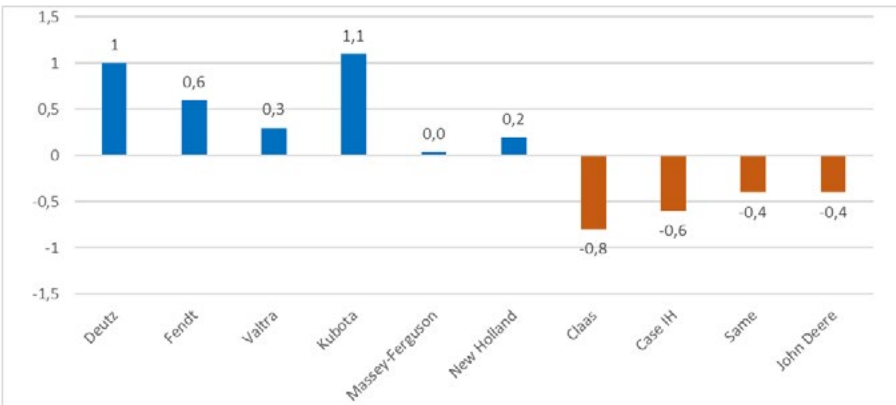

Fig. 8 Change in the satisfaction index of machinery dealers between 2023 and 2024 for each manufacturer, based on the quality of the manufacturer-dealer relationship (own editing, Source: **Fradier** 2024, CLIMMAR)

3.2. Results of the DSI survey in Germany

The survey described above is based on the European-wide database coordinated by CLIMMAR, with 11 countries represented. In addition, individual countries, e.g. Germany, i.e. CLIMMAR's German member LandBauTechnik e.V., also evaluate questionnaires in their "own competence", reflecting the satisfaction of German tractor dealers. (**Messerer** 2024a)

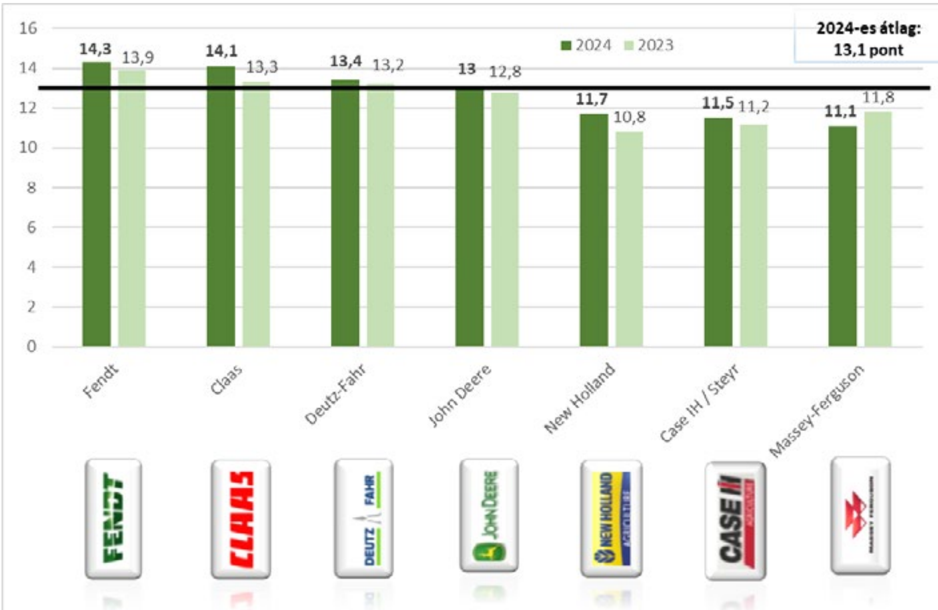

Fig. 9 Satisfaction index of machinery dealers for individual brands in Germany in 2024 and 2023 (own editing, Source: Agrartechnik 10/2024, **Messerer** 2024a)

These DSI results are country-specific and may differ slightly from the overall European trends. This is well illustrated by the German example, where it can be seen that, although based on a narrower population, the ranking is typical for the most popular tractor brands in Germany, but is close to the European ranking. One notable exception is that the list is not headed by Deutz-Fahr, but by Fendt, which has been the most popular in Germany for some time, followed by Claas in second place. (Figure 9). (Messerer 2024b)

4. Conclusions and recommendations

The survey is not intended to compare individual tractor brands. It is intended to provide a basis for constructive dialogue between manufacturers and dealers to address critical areas. The results of the questionnaire will serve as a tool for manufacturers to work with their sales network to identify and address areas for improvement, to the benefit of both parties. CLIMMAR strongly emphasises that the survey is not a rating of the products sold by the manufacturer. (CLIMMAR 2024)

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MODERNIZATION OF AGRICULTURE IN SERBIA: QUANTITATIVE ASSESSMENT OF IMPACTS ON RURAL DEVELOPMENT AND ENVIRONMENTAL CHALLENGES IN THE CONTEXT OF EU INTEGRATION

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Abstract. The modernisation of agriculture is a crucial factor in promoting rural development, while at the same time triggering various environmental and demographic changes. This paper provides a comparative quantitative assessment of the introduction of modern technologies in Serbian agriculture compared to EU practises, focussing on productivity, demographic trends and environmental indicators. while over 80% of farms in the EU use modern technologies such as GPS navigation, drones and automated systems, the adoption rate in Serbia is significantly lower - only 15% of farms use GPS, 5% drones and 10% automated systems. The data show that average wheat and maize yields in the EU are around 6.0 tonnes/ha and 8.0 tonnes/ha respectively, while in Serbia they remain at 4.5 tonnes/ha and 6.5 tonnes/ha. The cost-benefit analysis illustrates the differences in production efficiency and access to resources. Environmental indicators such as CO_2 emissions and pesticide use show that the environmental impact is higher in Serbia. The results emphasise the need for targeted investment, improved education and alignment with EU agricultural policy to promote sustainable rural revitalisation and technological progress.

Keywords: modern technology, rural development, environmental indicators, technological gap, sustainable agriculture

1. Introduction

Agriculture is the fundamental branch of the Serbian economy, which provides a significant contribution to the gross domestic product (GDP) and employs a large part of the rural population. However, agriculture faces numerous challenges that hinder its sustainable development, including deagrarianization, depopulation of rural areas and environmental degradation. The decrease in the number of the working population in rural areas, especially among young people, is a serious problem because it leads to a decrease in production and a decrease in competitiveness on the global market. Also, intensive agricultural production without adequate ecological practices results in soil degradation, reduction of biodiversity and pollution of water resources. (Stojanović & Radosavljević, 2021 ; Stojanović & Miljković, 2021).

In this context, the process of harmonization with European Union policies (Common Agricultural Policy - CAP) represents a key opportunity for Serbia (Jovanović & Petrović, 2020) . Adaptation to European standards not only opens up opportunities to improve competitiveness on the EU market, but also enables the application of new technologies and ecological practices that can improve productivity and long-term sustainability of agricultural production (Binswanger-Mkhize & McCalla, 2018). The emphasis in the modernization of agriculture is on the integration of modern technologies, such as precision agriculture, drones, automation and digital tools, which enable better resource management, reducing the impact on the environment and increasing efficiency (Marković & Kovačević, 2023). In this process, it is crucial to establish a balance between economic development and protection of natural resources, in order to ensure the sustainability of agricultural production and the quality of life in rural communities. This approach can become the basis for long-term development that not only increases the competitiveness of the agricultural sector, but also contributes to the preservation of the environment and the revitalization of rural areas.

2. Materials and Methods

The paper relies on the analysis of available literature, legislative documents, as well as studies from Serbia and the EU. Comparative analysis considers the successful practices of countries such as Ireland, Spain and Switzerland, while special attention is paid to the application of technologies such as precision agriculture and organic production. The methodology includes a qualitative analysis of the impact of modernization on rural development and environmental factors.

3. Results and Discussion

3.1 Impact of modernization on rural development

Modernization of agriculture through the introduction of modern technologies has a direct impact on increasing the productivity and competitiveness of agricultural production. According to the FAO (Food and Agriculture Organization) report, by introducing technologies such as precision farming systems, farmers can increase yields by 10-20% while reducing the use of water, pesticides and other resources, making production more sustainable (FAO, 2021). In Serbia, which is in the phase of modernization of agriculture, the application of mechanization such as tractors, harvesters and smart irrigation systems significantly reduces the dependence on human labor, while increasing efficiency and reducing costs (Popović & Živanović, 2020) . Data show that in the period from 2010 to 2020, investments in agricultural machinery in Serbia increased by 15%, while innovations in digitization, such as applications for monitoring climate and crop health, became available to smaller farmers as well. Ireland is an example of successfully integrating agriculture with non-agricultural sectors, especially through the development of green technologies and tourism (O'Connor & O'Neill, 2020). According to European Commission data, Irish rural regions have increased their gross domestic product by 40% since 2000 thanks to the diversification of economic activities, including renewable energy sources, agricultural tourism and manufacturing. This approach enabled the sustainable development of rural areas, reducing emigration and encouraging job growth.

Recent field research conducted in 250 farms in central and southern Serbia in 2024 shows that advanced technologies such as sensors and automation are only used to a limited extent. Only 12% of farmers report using sensors for crop monitoring, while 18% use some kind of automation, e.g. in irrigation or livestock feeding systems (Tab. 1).

Table 1. Survey results from agricultural holdings in Serbia (N=250)

Question / Indicator	Response Options	% of Respodents
Do you use crop monitoring sensors on your farm?	Yes	12%
	No	88%
Do you use any type of automation (e.g. irrigation, feeding systems)?	Yes	18%
	No	82%
What is the main barrier to technology adoption?	High equipment cost	54%
	Lack of technical knowledge	28%
	Poor internet/ infrastructure	12%
	No perceived benefit	6%
Would you consider using smart technologies in the next 5 years?	Yes	64%
	No	36%
Do you believe automation improves productivity?	Yes	71%
	No/Not sure	29%

Source: Authors

Main barriers cited were the high cost of initial equipment (54%), lack of technical knowledge (28%) and inadequate digital infrastructure (12%). Nevertheless, a promising 64% of respondents expressed interest in adopting smart technologies within the next five years, and more than 70% believe that such tools can improve productivity.

3.2 Deagrarianization and demographic trends

Deagrarianization is largely connected with the processes of urbanization and the reduction of the number of employees in agriculture. According to the data of the Republic Institute of Statistics of Serbia, in the last 30 years, the number of employees in agriculture decreased by almost 50%, and the share of agriculture in the gross domestic product (GDP) decreased from 12% to about 6%. This decline particularly affects rural communities, where young people are the main demographic segment that emigrates in search of better living and working conditions. Statistics show that in the period from 2002 to 2022, the number of inhabitants in rural areas of Serbia decreased by 15%, while the birth rate decreased by about 20% (Milijaš & Milić, 2023) . Demographic ageing, combined with the decrease in the number of young people remaining in the countryside, creates additional pressure on the social and economic systems of those areas. Data from the National Academy of Agricultural Sciences show that as many as 80% of agricultural farms in Serbia are run by the elderly population, while young people are increasingly withdrawing from the primary sector. These trends point to the need for urgent interventions, such as supporting young farmers and developing policies to revitalize rural communities. Through various funds and initiatives, the European Union offers subsidies for young farmers, which stimulates the return of young people to the countryside (European Commission, 2022) . For example, through the "Green Plan for Europe" program, investments of 10 billion euros are planned until 2027 in rural development, including agricultural modernization, youth education and infrastructure improvement, which can become a model for countries like Serbia (Marković & Vasiljević, 2022) .

3.3 Percentage participation of modern technologies in agriculture

Application of modern technologies in agriculture varies significantly between Serbia and the EU. While in the EU over 80% of agricultural farms use technologies such as GPS navigation, drones and sensors for crop monitoring, in Serbia that percentage amounts to only 25% (Vuković & Tasić, 2020). Lack of financial resources and insufficient education are the main obstacles to the wider implementation of these technologies in Serbia.

Table 2. Use of modern technologies in Serbia and the EU

Technology	Serbia (%)	EU (%)
GPS navigation	15	60
Drones	5	25
Crop monitoring sensors	5	60
Automated systems	10	50

Source: Eurostat, Agricultural Technologies in the EU (2022) ;
Statistical Office of the Republic of Serbia, Annual Agricultural Report (2022).

Differences in the use of technologies clearly show that Serbia is in the early stages of digitalization of agriculture (Tab. 2). While the EU is seeing significant benefits from the introduction of automation and digital tools, such as increasing work efficiency and reducing costs, Serbia must invest in the education of farmers and infrastructure. The use of GPS navigation, for example, allows more precise use of resources, which can reduce losses and costs.

Table 3. Use of modern technologies by farm tipe (N=250)

Farm type	% Using sensors	% Using automation
Family farms	8%	12%
Commercial farms	26%	38%
Mixed (semi-commercial)	14%	22%

Source: Authors

Results reveal low penetration of crop monitoring sensors (8%) and automation systems (12%), especially among small, family-run farms. Commercial farms demonstrate higher levels of adoption, with 26% using sensors and 38% employing automated systems (Tab. 3).

3.4 Cost-benefit analysis

Efficiency of agricultural production largely depends on the achieved yields and production costs (Swinnen, 2019) . The difference in these parameters between Serbia and the EU indicates the need for technological improvements in Serbia, as well as better access to subsidies and expertise.

Table 4. Analysis of yield and costs in cereal production

Indicator	Serbia	EU
Average wheat yield (t/ha)	4.5	6.0
Production costs (€/ha)	900	1200
Average corn yield (t/ha)	6.5	8.0
Production costs (€/ha)	850	1100

Source: FAO, Global Agriculture Report (2021) ;
Ministry of Agriculture of the Republic of Serbia, Yield Analysis (2022).

Yield analysis (Tab. 4) shows significant differences between Serbia and the EU. Although production costs are lower in Serbia, lower yields indicate the need to improve agrotechnical measures and introduce modern technologies. EU countries achieve higher

yields thanks to the integration of precision agriculture, better access to subsidies and more intensive professional support
(OECD, 2021).

One of the key success factors in the EU is the application of precise techniques that enable the optimization of resources, such as water and fertilizers. For example, "as-needed" irrigation reduces water loss and increases crop efficiency. Also, the use of high-quality seeds and integrated plant protection systems contributes to higher yields and long-term sustainability
(Đorđević & Jovanović, 2019) .

In Serbia, it is necessary to develop strategies that will include the education of farmers, strengthening of local infrastructure and increasing the availability of subsidies for technologies. Without these steps, the agricultural sector will continue to lag behind European standards.

3.5 Environmental challenges

Modern agriculture faces pressures to maintain a balance between productivity and environmental protection. Intensive use of pesticides, herbicides and mineral fertilizers endangers biodiversity, pollutes water resources and reduces soil quality. Overexploitation of irrigation water can lead to a decrease in the availability of this key resource.

In addition, greenhouse gas emissions from agricultural production, such as methane from animal husbandry and nitrous oxide from fertilizer application, contribute to global warming. Intensive farming systems can also cause soil erosion and loss of organic matter, which reduces productivity in the long term.

Table 5. Ecological data for Serbia and EU

Ecological indicator	Serbia	EU
Average CO_2 emission (t/ha)	1.2	0.8
Use of pesticides (kg/ha)	4.0	2.5
Organic matter loss (%)	20	10

Source: European Environment Agency (EEA), State of the Environment in the EU (2021).
Ministry of Environmental Protection of the Republic of Serbia, Impact of Agriculture on the Environment (2022).

Ecological data (Tab. 5) indicate serious challenges in Serbia. Higher CO2 emissions and more intensive use of pesticides lead to soil degradation and pollution. The EU is successfully reducing these negative effects through the application of agro-ecological measures and subsidizing sustainable practices (European Environmental Agency, 2021). Serbia could adopt these models in order to improve its environmental policy.

4. Conclusions

Modernization of agriculture represents a key chance for improving the quality of life in rural areas, but its success depends on a careful balancing of economic, ecological and social goals. Properly implemented modernization processes can lead to increased productivity, reduced costs, conservation of resources and creation of new jobs, which will enable the long-term development of these communities. However, in order to achieve sustainable development, it is necessary that modernization is not exclusively directed towards technological innovation, but that it is simultaneously dedicated to the preservation of natural resources and the improvement of social living conditions. Key recommendations include investing in education and training of the local workforce for the application of modern technologies, as well as strengthening cooperation between agricultural producers, scientific institutions and government authorities. Also, it is important to promote sustainable agriculture and implementation of ecological practices that will reduce negative effects on the environment, such as excessive use of pesticides and fertilizers , thus enabling the long-term sustainability of agricultural systems. Strong institutional support and engagement of local communities are key to a successful transition towards modernization and sustainable rural development. Supporting young farmers, facilitating access to subsidies and developing markets for organic products and ecological technologies can further motivate young people to stay in the countryside and start their own production activities. When these aspects are connected in a comprehensive approach, the modernization of agriculture can become the main driver of sustainable development of rural communities, bringing benefits both for the economy, and for society and the environment.

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THE INFLUENCE OF BIOSTIMULATORS AND BIOPROTECTORS ON THE QUALITY AND HEALTH STATUS OF GRAPES OF THE ŽILAVKA VARIETY

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Abstract. Unfavorable agro-ecological circumstances for grape agriculture have emerged in recent years as a result of climate changes, such as high air temperatures and a lack of precipitation. To counteract the negative repercussions, biostimulants are indicated for usage in plantations that have experienced stressful events such as drought, frost, nutrient deficiency, and plant disease. Furthermore, the usage of silicon-based preparations alleviates stress caused by insects, infections, and climate change. An experiment was conducted on Žilavka vines at a family farm in Kočina, near Mostar, during the 2025 crop year. Seven treatments were used to assess the impact of various preparations. To assess the influence of different kinds on mechanical composition, the weight of bunches, petioles, and berries were examined, as well as the sugar and acid content of grapes. Plasmopara viticola was also present this year, along with Lobesia botrana; both species caused serious damages. Every day, the vineyard's air temperature and precipitation were measured. Statistical data analysis using the ANOVA test revealed substantial differences between the variants, whereas the LSD test allowed for accurate comparisons of individual variants. The results demonstrate that Variant 5 significantly increased the weight of the bunches compared to the other treatments, although Variants 2 and 4 had a higher sugar content, indicating a varied effect of the preparation on the examined grape characteristics.

Keywords: grapevine, stress, biostimulators, sugars, acids

1. Introduction

The grapevine (Vitis vinifera) is an agricultural crop whose primary product, grapes, is consumed as food or processed into various other products. The largest vineyard areas and winemaking centers in Bosnia and Herzegovina are located within the municipalities of the Herzegovina-Neretva Canton. Among the three Herzegovinian wine-growing regions, the Mostar vineyard region is the most significant, accounting for about 90% of the total vineyard area. It is best known for cultivating the indigenous grape variety

Žilavka, which holds great economic importance due to the production of wine that is highly valued both domestically and internationally. Some of the most important agrobiological characteristics of the Žilavka variety include its ripening period in the third epoch, classifying it as a mid-late variety; normal and regular fertilization; and preference for loose, gravelly-stony, moderately fertile, warm, and deep soils. The variety is moderately resistant to low temperatures, more susceptible to downy mildew than to powdery mildew, and during the ripening period, especially in rainy conditions, it is sensitive to gray mold [1].

In addition to soil and climatic conditions, achieving high grape yields and good quality largely depends on temperature and climate factors. The Herzegovina region is particularly suitable for grapevine cultivation due to its high cumulative temperatures during the growing season, exceeding 4,800 °C, and mild winters, where the absolute minimum rarely drops below -10 °C [2]. Temperatures during the ripening period have a significant impact on grape quality, as they influence the key biochemical processes, sugar accumulation, and the breakdown of organic acids. When ripening occurs under high average daily temperatures, grapes generally accumulate a high sugar content, but a larger amount of organic acids is simultaneously degraded. Conversely, under lower temperatures, grapes tend to accumulate less sugar while retaining a higher acid content. Air temperature, combined with adequate moisture, also plays a crucial role in the development of grapevine diseases.

The optimal annual rainfall for grapevine cultivation ranges from 700 to 800 mm, while the minimum required amount is considered to be 400-500 mm of annual water equivalent [2]. The water requirements of grapevines vary depending on the growth stage. Adequate moisture is particularly important during the phase of intense shoot growth and during the period of rapid berry development.

However, excessive moisture can be highly detrimental, as heavy rainfall during flowering and fertilization may result in poor pollination, especially in varieties with functionally female flowers. Associated phenomena, such as drops in temperature and reduced sunlight, can lead to insufficient nutrition of the inflorescences, producing loose clusters. Following a prolonged drought, high rainfall can cause berry skin cracking, which provides ideal conditions for the development of *Botrytis cinerea*. High rainfall is also undesirable during grape ripening and while preparing the vines for the winter period. The occurrence of many grapevine diseases is closely linked to both the amount and the distribution of rainfall during the growing season. For instance, *Plasmopara viticola* can be destructive only in areas with high rainfall or high relative humidity during the vegetation period. The development of *Plasmopara viticola* requires free water on the leaf surface, such as droplets from rain, dew, or fog, or extremely high relative humidity. Infection by *Botrytis cinerea* also directly depends on the presence of water and temperature. Rain negatively affects the development of *Uncinula necator* because it washes away conidia and destroys fungal colonies on infected grapevine organs.

Grapevines require sunlight in all phenophases of development. Light is especially critical for the differentiation of flowering buds, as winter buds developing under good sunlight conditions carry a higher number of potential grape clusters. During ripening, a greater number of sunny days accelerates sugar accumulation, and sun-exposed clusters exhibit better berry coloration. The development of certain pathogens, such as *Uncinula necator* and *Plasmopara viticola*, is influenced by light, although its effect is secondary to temperature and rainfall.

In recent years, due to climatic changes, unfavorable agroecological conditions have been observed during grapevine cultivation, such as high air temperatures and a lack of rainfall.

To mitigate the negative effects, the application of biostimulants is recommended in vineyards that have experienced stressful conditions such as drought, frost, nutrient deficiencies, and plant diseases. Biostimulants used in agriculture encompass a wide range of formulations based on various compounds, substances, and other types of products, including microorganisms, micro- and macronutrients, enzymes, trace elements, plant growth regulators, elicitors, as well as microalgal extracts. These are applied to plants or soils to enhance physiological processes and, consequently, improve crop productivity and quality [3].

Amino acid-based biostimulants or seaweed extracts represent a simple technological measure that can be applied either preventively, before the onset of stressful conditions, or curatively, to enhance plant recovery after damage has occurred. The use of biostimulants such as amino acids and seaweed, targeted foliar fertilization with specific elements (magnesium, copper, potassium), the application of silicon (Si), different types of clay (muscovite and kaolinite), and special polymers that enable water adsorption and retention in the soil has been described [4]. Seaweed extracts, particularly from the brown alga *Ascophyllum nodosum* (L.), are recognized as one of the main groups of biostimulants with significant agricultural potential. Currently, the application of biostimulants of various origins is considered an innovative approach for preventing grapevine diseases while improving grape and wine quality [5]. Biostimulants can be classified as follows: humic substances, seaweed extracts, complex organic materials, amino acids and other nitrogenated compounds, antitranspirants, beneficial chemical elements, inorganic salts including phosphorus, chitin and derivatives of chitosan[18].

According to [6], the use of biostimulants can support sustainable agricultural practices, as their application may enhance nutrient use efficiency, reduce fertilizer losses, increase overall yield, and produce high-quality crops. Their studies demonstrate that biostimulant application positively influences the agronomic performance of olive and grapevine plants by improving olive oil quality and increasing grape yield. Specifically, they reported the beneficial effects of foliar application of seaweed extracts on fruit quality across several black grape varieties under diverse climatic conditions, ranging from cold to warm vineyard regions. This represents the first documented evidence of the positive impact of biostimulants derived from the brown seaweed *Ascophyllum nodosum* on fruit ripening dynamics and quality at harvest [7]. Conversely, other studies have noted that crops treated with biostimulants may respond differently depending on varying climatic conditions [5, 8].

Foliar amino acid-based biostimulants (proline and tryptophan) enhance the photosynthetic activity of plants, helping seedlings quickly overcome slowed growth caused by unfavorable environmental conditions [9]. Table and wine grapes are among the main crops on which biostimulants are applied in Europe [18].

2. Materials and Methods

The research was conducted in 2025 on a family-owned vineyard located in Kočine near Mostar (43.30735, 17.85014). The vineyard, covering an area of approximately 0.1 ha, is planted with the Žilavka variety, situated on gentle slopes and oriented towards the southwest. The planting distance is 1.2 × 1.2 m, and the training system is a double-cordon. The experiment was arranged in a randomized block design with seven variants, each consisting of ten vines. The experimental treatments were as follows: Bioplex, Trazex, Bioplex, AgroK, and Barrier; Bioplex + Inex; Trazex + Agro K; Barrier; Amiksol + Slavol; Aleox; and Control (no treatment).

All treatments were applied using a 20 L SOLO 435 backpack sprayer, and the preparations were used at the recommended concentrations according to the manufacturers' instructions. The treatment schedule for each variant is presented in Table 1.

Table 1. Application schedule of treatments by experimental variants

Variants						
Date	1	2	3	4	5	6
22.04.2025	Bioplex	Bioplex+Inex	Trazex+ Agro K	Barrier	Amiksol+ Slavol	Aleox
10.05.2025	Trazex		Trazex+ Agro K	Barrier	Amiksol+ Slavol	Aleox
25.05.2025	Bioplex		Trazex+ Agro K	Barrier	Amiksol+ Slavol	
27.05.2025		Bioplex+Inex				
12.06.2025	Bioplex		Trazex+ Agro K	Barrier	Amiksol+ Slavol	Aleox
27.06.2025	Bioplex		Trazex+ Agro K	Barrier	Amiksol+ Slavol	Aleox
15.07.2025	Agro K		Trazex+ Agro K	Barrier	Amiksol+ Slavol	
19.07.2025		Bioplex+Inex				
01.08.2025				Barrier	Amiksol+ Slavol	Aleox

Agrotechnical practices were carried out following the standard procedures of the farmer and included, among other measures, soil cultivation with a rotary tiller, the application of copper-based fungicides to control *Plasmopara viticola*, the installation of pheromone traps for the grapevine moth (*Lobesia botrana*), and other treatments. Air temperatures in the vineyard were measured daily using a thermometer, and rainfall was recorded using a rain gauge with a measuring scale. During the growing season, the health status of the grape clusters was assessed on several occasions through visual inspection, based on symptoms and the level of infection expressed as a percentage.

At harvest, yields were determined by weighing the grapes from each vine (10 per variant) as well as recording the total number of clusters per variant. On representative clusters (15 per variant), cluster weight was measured, after which the berries were manually separated from the stems. The berries were collected in separate containers and weighed again, and the weight was recorded. The same procedure was applied to the remaining stems (rachis), which were also weighed separately after separation. In this way, three parameters were obtained for each sampled cluster: total cluster weight, berry weight, and stem weight.

Harvested grape samples for determining total acidity and sugar content were separately packed in plastic bags and transported to the Agromediterranean Faculty laboratory in Mostar, where the analyses were performed. Approximately 1 kg of grapes was sampled from each variant. In the laboratory, the grapes were crushed and gently pressed to obtain must, which was then filtered to separate the clear juice. The obtained juice was used for refractometric measurements, with one drop placed on the prism of the refractometer in three repetitions to ensure reliability and precision of the results. Using the same procedure, samples for determining grape acidity were prepared and analyzed by titration with a sodium hydroxide solution of known concentration in the presence of phenolphthalein as an indicator

All collected data were statistically processed using one-way analysis of variance (ANOVA), which allows for the assessment of whether statistically significant differences exist between groups for all examined parameters. To compare the variants, the LSD test ($p = 0.05$) was applied, enabling the identification of variants that differ statistically and determining the effect of the variants on the mechanical and chemical characteristics of the grapes.

Although Variant 1 (Bioplex, Trazex, Bioplex, Agro K, and Barrier) and Variant 3 (Trazex + Agro K) were included in the experiment, data for these variants could not be collected or included in the statistical analysis due to damage to the clusters caused by flocks of blackbirds.

3. Results and Discussion

For the analysis of climatic conditions during the research period, data from on-site monitoring at the Kočine location were used for the period from March to August 2025. The following parameters were recorded: average, maximum, and minimum air temperature (°C), as well as the amount of precipitation (l/m^2). The data presented in Table

2 show that the highest average and maximum air temperatures were recorded in July, while the minimum temperature was, as expected, the lowest in March. The highest average precipitation was measured in March, May, and August, whereas no rainfall was recorded in June.

Table 2. Average values of temperature and precipitation in 2025

Month	T avg (°C)	T max(°C)	T min(°C)	P avg (l/m2)
March	13.1	17.56	8.03	8.8
April	17.0	21.85	10.64	1.6
May	20.2	25.23	13.41	5.8
June	29.5	35.56	20.12	0
July	30.0	35.7	21.5	1.9
August	27.9	34.3	21.1	4.5

Weather conditions for grape production were favorable, without prolonged drought periods or extreme temperatures. During the summer, high temperatures combined with low air humidity and direct sunlight in Herzegovina can cause damage in the form of sunburn on the berries. Although there was no rainfall in June, the grapevines did not experience drought because there had been significant precipitation in the preceding period, allowing the vines to function normally. At the end of August and the beginning of September, heavy rainfall was recorded on several occasions while the grapes were in full ripening stage.

Air temperature, together with a favorable amount of moisture, has a significant impact on the occurrence of grapevine diseases. The Žilavka variety is sensitive to downy mildew, less to powdery mildew, and extremely susceptible to botrytis, especially during warm and rainy days when infections can be widespread [10]. Regular monitoring revealed the appearance of downy mildew (*Plasmopara viticola*) at the beginning of June, following favorable weather conditions. Considering that only four hours of dew or leaf wetness at suitable temperatures are sufficient for downy mildew infection, the conditions for the development of Plasmopara viticola were favorable at the end of May and the beginning of June, when symptoms were observed on all variants to varying degrees.

The percentage values of downy mildew symptoms on grapevines in June 2025 are presented in Table 3.

Table 3. Leaf damage caused by Plasmopara viticola

Variants						
1.Bioplex, Trazex, Bioplex, Agro K, and Barrier	2.Bioplex+ Inex	3.Trazex+ Agro K	4.Barrier	5.Amiksol+ Slavol	6.Aleox	7.Control
11%	14%	12%	10%	13%	13%	15%

Spring 2025 can be characterized as quite favorable for the development of downy mildew, considering that it rained frequently in May and temperatures remained within the optimal range for downy mildew development. Grapevines from the variants treated with the bioprotector Barrier (1 and 4) had the lowest percentage of leaves showing downy mildew symptoms, while, as expected, the control showed the highest. However, the deviations were very small, so we cannot conclusively determine that the application of biostimulants and bioprotectors had an impact on the occurrence of downy mildew. The grapevine moth (*Lobesia botrana*) was observed, causing some damage to the grapes, but this was insignificant compared to the impact of birds (blackbirds), which, in a short period during August, completely destroyed part of the vineyard, including the two variants closest to their attack. Unfortunately, the grape clusters were completely destroyed or damaged, so we could not carry out measurements on variant 1 (Bioplex, Trazex, Bioplex, Agro K, and Barrier) and the variant with the combination Trazex + Agro K.

3.1 Grape Yield, Mechanical, and Chemical Composition

At the time of technological maturity of the grapes, yields, grape characteristics, as well as sugar and acid content were determined. The results of the measurements of the mechanical composition of the grapes are presented in Table 4.

Table 4. The results of the measurements of the mechanical composition

Variants	Total grape weight per variant (g)	kg/vine	Number of clusters on 10 vines
1. Bioplex, Trazex, Bioplex, Agro K, and Barrier	/	/	/
2.Bioplex + Inex	10.348	1	75
3. Trazex + Agro K	/	/	/
4.Barrier	10.425	1	74
5.Amiksol + Slavol	12.171	1,2	86
6.Aleox	13.329	1,3	96
7.Control	12.601	1,2	89

From Table 4, it can be seen that in the conducted study on 10 vines per variant, differences were observed in the number of grape clusters, yield per vine, and total yield. The lowest number of clusters was recorded in the second (Bioplex + Inex) and fourth (Barrier) variants (75 and 74 clusters, respectively), both of which had a yield slightly above 10 kg per variant. The highest number of clusters was found in variant 6 (Aleox), with a total yield of 13.3 kg, which was also the highest value in the study. The other variants had a total yield of around 12 kg per variant. The average weight per vine ranged from 1 to 1.3 kg.

Grape yields in the Herzegovina-Neretva Canton (HNK) vary from year to year. Table 5 presents statistical data (2020-2024) showing the total yield (t) and yield per vine (kg) of grapes in the Herzegovina-Neretva Canton [11].

Table 5. Grape production in HNK (2020-2024)

Year	Total production (t)	kg/vine
2020	35544	3.5
2021	33533	3.4
2022	40058	3.9
2023		
2024	19271	
27644	1.9	
2.9		

As can be seen from the data presented in Table 5, grape yields in the Herzegovina-Neretva Canton over the observed five-year period were not consistent. The lower yield in 2023 compared to the previous year was caused by unfavorable weather conditions. In the production year 2022, the highest yields were recorded, with a total of 40,058 t and the highest yield per vine of 3.9 kg.

Grape yields in the Municipality of Mostar, according to the same source, over the five-year period 2020-2024 were as follows by year: 8,983 t, 9,405 t, 16,416 t, 4,435 t, while no data for Mostar were available for 2024. The average grape weight per vine in the Mostar area ranged from a minimum of 1.9 kg per vine in 2023 to the maximum yield of 3.9 kg per vine in 2022, which does not correspond with the results from the experimental trial (1 to 1.3 kg per vine).

Based on information from local media as well as conversations with small and large grape producers, it can be noted that vineyard productivity in 2025 increased by 25-30% compared to the previous year.

Numerous factors influence grape yield, including the variety, number of vines per hectare, training system, vineyard age, applied agricultural and viticultural practices, as well as climatic conditions throughout the year.

From the research results and literature data, it can be concluded that grape yields in 2025 were below average, which can be attributed to the age of the vineyard (35 years) and inadequate agronomic practices, which, among other factors, contributed to the occurrence of downy mildew that significantly reduced the yield. Despite the application of biostimulants and favorable weather conditions, the vineyard yield underperformed, indicating to the agricultural producer the inadequate use of protective agents and viticultural practices in the vineyard.

3.2 Cluster, Pedicel, and Berry Weight

To assess grape quality, the proportion of berries and pedicels in the total cluster weight was calculated, as their ratio directly affects yield as well as the technological characteristics of grapes in further processing.

The results of the measurements of cluster, pedicel, and berry weight are presented in Table 6.

Table 6. Summary of basic statistical parameters by variant for cluster characteristics

Variants	Cluster Weight (g)	Pedicel Weight (g)	Berry Weight (g)
2. Bioplex + Inex	148.53a	10.47a	139.33a
4. Barrier	145.93a	9.60b	136.13ab
5. Amiksol + Slavol	140.26b	9.27b	131.00b
6. Aleox	140.66b	9.67b	131.80b
7. Control	147.33a	9.73b	137.67a
$LSD_{0.05}$	6.17	0.76	5.73

The highest cluster weight was recorded in Variant 2 (Bioplex and Inex), which was statistically significantly higher than in Variants 5 and 6, while the difference in cluster weight between Variant 2 and Variants 4 and 7 was not statistically significant. The lowest cluster weight was observed in Variant 5, slightly lower than in Variant 6, and the difference between them was not statistically significant. The highest average pedicel weigh was observed in Variant 2 (10.47 g), statistically highly significant in relation to all the other variants which did not differ from each other significantly.

The highest average berry weight was recorded in Variant 2 (139.33 g), which was statistically significantly higher than in Variants 5 and 6, while it did not differ statistically significantly from Variants 7 and 4.

Table 7. Results of one-way ANOVA analysis for cluster weight

Source of Variations	SS	df	MS	F	P-*vaule*	F *crit*
Between Groups	884.32	4.00	221.08	3.06*	0.02	2.50
Within Groups	5052.26	70.00	72.18			
Total	5936.587	74				

Table 8. Results of one-way ANOVA analysis for stem weight

Source of Variations	SS	df	MS	F	P-*vaule*	F *crit*
Between Groups	11.65	4.00	2.91	2.66*	0.04	2.50
Within Groups	76.53	70.00	1.09			
Total	88.18	74				

Table 9. Results of one-way ANOVA analysis for berry weight

Source of Variations	SS	df	MS	F	P-*value*	F *crit*
Between Groups	798.58	4	199.65	3.21*	0.02	2.50
Within Groups	4350.8	70	0. 62			
Total	5149.38	74				

Observing the tested variants in the experiment, it can be concluded that the best results for all three examined parameters were achieved by Variant 2, that is, the application of Bioplex and Inex.

The results of cluster weight in all variants were below most literature sources, which report cluster weights ranging from 150-200 g [1, 16]. However, some sources indicate that cluster weight can vary within a slightly wider range, from 120-250 g [10]. The application of biostimulants in grape production in Italy increased yield quantity but not grape quality [6]. During a two-year study [12], significant differences in the ampelometric characteristics of the Žilavka variety were observed, with an average cluster weight of 213.05 g in 2014 and 197.80 g in 2015, which is considerably higher than the results of our research. Studies conducted in California, USA, suggest that certain biostimulants improve the quality of table grapes, achieving greater uniformity in berry color and size [17].

3.3 Sugar and acid content

The sugar and acid content in the study of the Žilavka variety in 2025 is presented in Table 10.

Table 10. Chemical properties of Žilavka grape variety in 2025

Variants	Sugar (%)	Acid (g/l)
2. Bioplex + Inex	20.67b	6.2ab
4. Barrier	20.00c	7.4a
5. Amiksol + Slavol	21.77a	5.2b
6. Aleox	20.30bc	5b
7. Control	20.00c	6.2ab
LSD0,05	0.56	1.74

From Table 10, it can be seen that the tested variants of the Žilavka grape variety exhibited different values of sugar and total acid content. The highest sugar content was recorded in Variant 5 (21.77 %), which was statistically significantly higher compared to all other variants. The lowest sugar content (20.00 %) was observed in Variants 4 and 7, with no statistically significant difference from Variant 6. The highest acid content in grapes was found in Variant 4, which was statistically highly significant compared to Variants 5 and 6, while it did not differ statistically significantly from Variants 2 and 7. The lowest acid content was observed in Variant 6, but this difference compared to Variants 2 and 7 was not statistically significant. Tables 11 and 12 present the results of the variance analysis, showing that the tested factor had a statistically highly significant effect on the examined parameters, sugar and acid content (F > F crit).

Table 11. Results of one-way ANOVA for grape sugar content

Source of Variations	SS	df	MS	F	P-*value*	F *crit*
Between Groups	6.48	4	1.62	15.70**	0.00026	3.50
Within Groups	1.03	10	0.10			
Total	7.51	14				

Table 12. Results of one-way ANOVA for grape acidity

Source of Variations	SS	df	MS	F	P-*value*	F *crit*
Between Groups	11.04	4	2.76	2.76**	0.09	3.48
Within Groups	10	10	1			
Total	21.04	14				

At full ripeness, under favorable conditions, grapes accumulate between 20% and 24% sugar, sometimes even up to 28%, while total acids range from 5 to 8 g/l [10]. In a study [13] conducted in 2011 on the Žilavka variety, sugar content ranged from 20.1 to 21.1%, indicating that 2011 was a favorable year for producing high-quality wines. Total acid content in Žilavka grapes ranged from 4.3 to 5.7 g/l, which can be considered low and insufficient for safe processing into high-quality wines. A study of sugar content in Žilavka grapes grown at the Blizanci site in the Mostar wine region showed a significantly higher sugar content in the 2002 harvest (average 20.4%) compared to the 2003 harvest (18.5%). Grapes from the 2003 harvest also had significantly higher total acid content (7.6 g/l) compared to grapes from 2002 (6 g/l) [14]. In another study [15], the total acidity of Žilavka grape must ranged from 6.2 to 6.5 g/l.

4. Conclusion

The application of biostimulants in viticulture is becoming justified due to the negative effects of climate change, as indicated by numerous studies. It is necessary to study their effectiveness on different grape varieties under various climatic and soil conditions.

The weather conditions for grape production in Mostar during 2025 were favorable, without prolonged drought periods or extreme temperatures. However, at the beginning of June, Plasmopara viticola appeared, preceded by favorable weather conditions. Variants 1 and 4, treated with the bioprotector Barrier, showed the lowest percentage of leaf infection, while the highest infection occurred in the control variant 7. The greatest problem was caused by birds in August, which destroyed a part of the vineyard, including two experimental variants that could not be included in the results.

Variant 2 (Bioplex + Inex) performed best in terms of cluster weight, stem weight, and berry weight. Žilavka grapes from the 2025 experiment had sugar content (20-21.7%) and acidity (5-7.4 g/l) consistent with literature data and the reputation of Žilavka as a variety suitable for premium wines. Total yield and yield per vine, as well as the number of clusters per vine, were below average, which can be attributed to the occurrence of downy mildew, the age of the vineyard, and inadequate agrotechnical measures.

This study did not identify a single biostimulant that was superior for all parameters, but it should be noted that it was a relatively small experiment conducted over one year at a single location. Considering also the advanced age of the vineyard and the irregular application of agrotechnical measures, this research can be considered preliminary. Further, larger studies will be conducted to reach more definitive conclusions.

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OPTIMIZING THE USE OF PESTICIDES IN PERMANENT PLANTATIONS – LowVolPest

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Abstract. The project proposal envisages a four-year study (2 years' apple orchard and 2 years' vineyard) to investigate the influence of technical and technological factors of pesticide application on the main characteristics of the study: Residues of active pesticide substances in the fruit, occurrence and spread of pests, fruit quality, and deposition and drift of the spray. The technical and technological factors of the application are the spraying rate, the spray concentration and the nozzle type with its sub-factors. The spraying rate is determined according to the TRV method (tree row volume) and a 50% reduction, while the concentration is determined according to the recommended (FIS registration) and its 20 and 40% reduction. According to the technological map for the protection of permanent plantations, two types of nozzles are used for spraying: Standard TR and Air-Injector ITR. The residues of the active substances are determined using the liquid chromatography with mass spectrometer (LC-MS/MS) method in an accredited laboratory, while the quality of the fruit and the occurrence and development of the pests are determined in the Faculty of agrobiotechnical sciences central laboratory. The deposit and spray drift are determined using the spectrophotometric method defined by the ISO 22866:2005 standard. The field trial should provide information on whether it is possible to reduce the application rate and concentration of sprays (low-volume pesticide management) and at the same time improve the quality of the fruit with the same or better

biological effect on the pests. In addition, the improved quality of spraying will reduce drift, which will have an impact on better pest control and the possibility of reducing the number of applications.

Key words: sprayer, pesticide, residues, nozzles, pests, spraying

1. Introduction

This manuscript is presenting a scientific project funded by the EU funds 581 – Recovery and Resilience Mechanism through the NextGenerationEU platform under the national NPOO program. Therefore, the text represents a four-year scientific project starting on 1 October 2025. It explains the reasons for applying for the mentioned project, the main research objectives, the research methodology and the expected research results with the application projection.

The intensity of agricultural production in modern farming systems has the task of achieving a high yield of a certain crop with corresponding quality. Intensity follows modern technological progress, and by utilizing all modern technologies, producers can indeed achieve high yields in all areas of agricultural production. When it comes to the quality of agricultural products, the paradigm becomes much more complicated. The quality of fruits can refer to several factors that we observe, namely: pomological, physiological, morphological, technological, organoleptic, phytosanitary, economic, etc. Of all the types of fruit quality listed, the market and farmers demand excellent results, especially in the economic characteristics, which refer to the classification of the fruit and the categorization in the extra class, which also achieves the highest price (Ministry of Agriculture, NN 114/2008). The first prerequisite for achieving such quality is a product without scab and spotty damage (damage caused by plant diseases), which can completely downgrade the fruit. In order to meet market demands and achieve the desired results, growers have started to apply technological protection maps that provide for even more than 25 pesticide applications during the growing season (this is especially true for apple orchards, which are one of the resources of the project proposal). The protection plan can be viewed at several commercial pages like at “Agroklub” and “Fitopromet”

Based on the above examples, we conclude that these production technologies, the fruits are loaded with residues of pesticide active substances that exceed the permitted MRLs (maximum residue levels) - non-compliance with phytosanitary quality (Elsavier, 2016, Ahmadi, et al., 2024). The MRLs (EU pesticide database) for the individual active substances are set and amended at EU level so that they can be applied by the individual member states. The results of the project proposal are commented on the basis of this database and the applicable Croatian regulations and laws. The described situation is a paradigm of current production technologies in permanent plantations, and the system of regulation and control of pesticide residues in the Republic of Croatia is not sufficiently coordinated (549 samples for the entire Republic of Croatia, Croatian Agency for Agriculture and Food), and very few samples are analyzed for residues of active substances without complete analytical reports being available, both from domestic production and from imports (Ministry of Agriculture, NN 79/2008).

In the Republic of Croatia, there is no comprehensive multidisciplinary scientific research on the above-mentioned topic, and with this project proposal, empirical results will be obtained by copying current technological maps of plant protection into an experimental design, and as one of the research results, residues of active substances in fruits will be determined. From all this it can be concluded that the topic described is current, poorly researched, poorly regulated and associated with very little scientific research from direct production.

2. Material and methods

The research and project proposal is designed as a four-year (2 years' apple + 2 years' vineyard) field trial with laboratory completion to obtain empirical results using already established and proven scientific methods. Several working hypotheses can be derived from the research objectives, the title and the expected results, several working hypotheses can be defined:

- The current technological map of permanent crop protection with the recommended concentrations and spraying rates controls the development and spread of pests well, but with active pesticide substance residues above the permitted MRL levels;
- Reducing the spraying rate and the recommended concentration of sprays will also control the pests satisfactorily during the growing season, with the obligation to improve the quality of spraying (different nozzle types and technical settings), but with active substance residues below the MRL levels;
- Fruit quality is better in treatments where lower amounts of pesticides are sprayed (either spraying rates or concentrations);
- The growing season plays an important role in the application of spray application;
- Technical factors in the application of sprays play an important role in the deposition and drift of sprays.

The above working hypotheses will be tested, as already mentioned, in the context of field research, and the experiments will be set up as a standard three-factor design. The first factor is of a technical-technological nature and relates to the ***spraying rate (1)***. The application rate is a factor that is adjusted according to the needs of the plantation and its development phase (lower spraying rates are set at the beginning of vegetation) and higher application rates at the end of vegetation. The spraying rate (Tadić, V., 2013) depends primarily on the condition of the leaf area (LAI index) and the leaf density (LAD index). It is usually calculated using the TRV method (tree row volume), which must result in good deposition and surface coverage and minimal air and soil drift of the spray (UW Fruit Programme, Wisconsin Fruit). The most important technical factors that strongly influence the adjustment of the spraying rate are the ISO nozzle number, the operating speed, the operating pressure, the number of nozzles in operation and the row spacing of the plantation. The project plan is planned on two levels – two sub-factors in relation to this factor. The first sub-factor is the spraying norm adjusted according to the procedure described (LAI and LAD) and the second sub-factor is the spraying norm reduced by 50%.

The second factor of the study is the *concentration of the spray (2)*, i.e. the concentration of the active substance of the pesticide in the water (Milton D., Taylor, 2020). This technological factor of the field trial was planned in three levels (three sub-factors), namely: recommended (100%) concentration in relation to the registration of the active substance (FIS system) on the type of plantation in the study (2.1.); 80% concentration in relation to the recommended concentration (2.2.) and 60% concentration (2.3.).

The third factor in the study is the *type of nozzle (3)*. This technical factor (Tadić, V. et al., 2014) was planned in two levels (two sub-factors), namely: standard nozzle TR 80 (3.1.) and air injector nozzle ITR 80 (3.2.). The color of the nozzles, i.e. the ISO number, is adjusted according to the first factor of the trial – the spraying norm, and the nozzle type is the third factor of the study. If the nozzle has the same ISO number but a different type, this primarily relates to the spectrum of droplets produced by the nozzle (Tadić, V. et al., 2024). The TR nozzle produces a smaller droplet spectrum with potentially greater coverage of the treated surface (better biological effect of the active substance) and greater air drift (Figure 1a). The ITR nozzle (Figure 1b) produces droplets with a larger diameter (SVP – mean volume diameter 20-30 larger), which cover the treated surface less well but are less susceptible to drift. Table 1 shows schematic example of conducting research.

Figure 1a TR nozzle

Figure 1b ITR nozzle

Table 1 Research plan

	Apple orchard (2 y.)			Vineyard (2 y.)		
Spraying norm (1) (N_r – l ha^{-1})	TRV (1.1.)	50% TRV (1.2.)		TRV (1.1.)	50% TRV (1.2.)	
Concertation (2) (c - %)	100% (2.1.)	80% (2.2.)	60% (2.3.)	100% (2.1.)	80% (2.2.)	60% (2.3.)
Nozzle type (3) (n)	TR (3.1.)	ITR (3.2.)		TR (3.1.)	ITR (3.2.)	

*vegetation year (4)

The main characteristics of the research, i.e. the measurable parameters that are monitored in the field and later processed in the laboratory, are:

- Residues of active substances in fruits used in the technological map of plantation protection and in the experimental design (all active substances are determined by laboratory analysis);
- Occurrence and development of pests during the growing season and on the fruit (infection indices);
- Fruit characteristics (morphological, pomological, physiological, economic, etc.);
- Deposit of sprays in the plantations;
- Spray application according to ISO 22866:2005.

Pesticide residues (1) as one of the characteristics of the research are determined in the fruits according to the research plan in accredited laboratories that easily determine the residues with their equipment and techniques. Laboratories that determine pesticide residues must have certificates in accordance with HRN EN ISO/IEC 17025:2017 (ISO/IEC 17025:2017; EN ISO/IEC 17025:2017). Using the methods mentioned, these laboratories also find minimal residues of active substances in fruit using two techniques LC-MS/MS and GC-MS/MS and provide data in mg kg-1 of the analyzed fruit with a comparison of the currently valid residues in the EU and the Republic of Croatia (EU pesticide database). The aforementioned standards use the technique of liquid chromatography (Cindrić, M., et al., 2009) with a mass spectrometer (LC-MS/MS) and gas chromatography (GC-MS/MS). These methods can be used to measure over 400 active substances in minimal concentrations.

Another feature of the study is the *occurrence and progression of pests during the growing season (2)* on fruits and leaves (infection indices). During the growing season, samples are taken from the plantations (fruits and leaves) according to the research treatments and the infection indices are analysed, commented and conclusions are drawn about the impact of each research treatment on the biology of the pests. The disease evaluation indices for apple and grapevine are used for a standardized evaluation of infection intensity under research and field conditions. For the evaluation of diseases such as apple scab *(Venturia inaequalis)*, a scale from 0 to 5 is often used according to EPPO standards, where 0 indicates the absence of symptoms and 5 means very pronounced symptoms with more than 75 % of the leaf area affected. For grapevines, a scale of 0-9 is used for powdery mildew *(Erysiphe necator)* and downy mildew *(Plasmopara viticola)* – according to the OIV (*Organisation Internationale de la Vigne et du Vin* - https://www.oiv.int/node), which rates the intensity of symptoms on leaves and grapes in detail. These scales are particularly useful in trials comparing different spraying strategies, such as differences in frequency, type of fungicide or application of biological preparations. Based on the results of the evaluation, it is possible to quantitatively assess the effectiveness of individual treatments, optimise plant protection and reduce the unnecessary use of plant protection products.

The third research property will be the *quality of the fruit (3)* from the permanent plantations in the research (two years of apples and two years of grapes). The assumptions contained in the working hypotheses and objectives of the research are that the economic/commercial characteristics depend largely on the individual research treatments (here damage to the fruit is meant - scab/spot/rot). The observation of the morphological characteristics of the fruit (size, shape, colour, hardness, calyx, etc.) will probably not differ greatly between treatments, while the pomological and physiological characteristics will vary greatly depending on the research treatments (Skendrović Babojelić, et al., 2014). As part of the pomological (morphometric) measurements of the apples, it is planned to carry out analyses that include the following: Yield, yield per tree, number of fruits, fruit weight, fruit height and width index, hardness, iodine-starch index and fruit colour according to the CIE LAB system. Analyses of the internal quality of the fruit are also planned: dry matter and acidity as well as spectrophotometric measurement of the vitamin C content, anthocyanins, total phenols and antioxidant activity. In the second part of the research to evaluate grape quality, the project proposal envisages carrying out the following analyses: Yield per vine, average grape mass per vine, sugar content, total acidity, anthocyanin and polyphenol content, antioxidant value, relative density of the must, pH value.

The fourth research property according to the project proposal is *the spray deposit (4)* in the plantation. The spray deposit (Petrović, D. et al., 2019; Petrović, D. et al., 2019) is a technical property of the application and represents a precisely defined concentration of the spray that is applied to a specific part of the canopy. The more evenly the deposition is distributed in the canopy, the better the biological effect of the pesticides and vice versa. The aim is to adjust the technical factors of application in the research plantations in such a way that the highest possible application rate is achieved. However, it can also vary greatly depending on a number of technical factors that are also taken into account in this project proposal (nozzle type, spray concentration and spray volume). The deposition is determined using the spectrophotometry method, whereby samples of different concentrations are collected on filter paper within the plantation. The dye tartrazine (which serves as a tracer, a dye with a precisely determined concentration) produces a spectrophotometric curve at 425 nm. The sampled filter papers were washed with 0.1 l of deionized water. After washing, the solution was pipetted into a quartz cuvette and the wavelength was read in a spectrophotometer. The values obtained were used to calculate the spray deposit (µg cm^{-2}).

Figure 2 Drift and deposit measurement in orchard

The fifth property of the research contained in the project proposal is drift (5). The term drift (Petrović, D., 2018) includes three phenomena: the evaporation of the spray due to high temperature and low humidity and the entrainment of the spray outside the plantation due to the high speed of movement or the high speed of the surrounding wind. We can conclude that drift is the opposite of deposition, i.e. if the spray deposition is weak or very small, then the occurrence of drift is increased. Various scientific sources emphasize and prove that this phenomenon is unavoidable; that in average applications it accounts for 30-40% of the spray volume (Petrović, D., 2018) and that it is the task of adjusting the technical factors of the application to minimize drift as much as possible. The methodology for determining drift is determined by the international standard ISO 22866:2005 (Figure 2) and the filter papers are processed using the same method as for deposition.

As a research feature, this group also includes the *vegetation year (6)*, which is an indicator of the weather conditions that influence the growth, development and spread of pests in the plantation.

3. Expected results

The main objectives of the project proposal include research into the effects of agricultural techniques (different types of nozzles) and crop protection technology (different concentrations and spray volumes) on the main characteristics of the study: residues of active substances in the fruit, protective effect on the occurrence and progression of pests, fruit characteristics and on the deposition and drift of pesticides. By varying the above factors in the field study, it will be possible to find out which treatment has the best effect on pests with residues below the authorized levels while ensuring satisfactory fruit quality, i.e. the possibility of reducing the standard and dosage of pesticides (low pesticide management) with the same or better biological effect on pests and a reduction in pesticide residues in the fruit over two years in two permanent plantations. For each plantation, pesticide deposition and drift will be analyzed in relation to the technical factors of the project proposal and, as the vegetation progresses in the second year, conclusions will be drawn about the influence of the growing season on the above-mentioned characteristics. According to the stated research objectives of the project proposal and the working hypotheses, it is realistic to expect some measurable indicators that will fulfill/disprove the working hypotheses. The project proposal contains several measurable research indicators that are expected to more or less confirm the working hypotheses, as follows:

(1) The current technological map for the protection of permanent crops with the recommended concentrations and spray rates controls the development and spread of pests well, but with active pesticides residues above the permitted MRL levels. Pest control with a 20% reduction in concentration and the same or lower spray rates will achieve the same biological effect as the recommended treatments with an efficiency of 70-80% - verified by fruit quality, residues of active substances and pest control indices;

(2) A reduction in spray volume will also result in satisfactory pest control during the

growing season, with a commitment to improve the quality of spray application (different nozzle types and technical settings), with active ingredient residues below MRLs. Pesticide residues in the fruit of permanent crops are expected to be reduced by 40-60% due to the use of technology with a 50% reduction in spray volume - which will be verified by fruit quality, residues of active substances and pest control indices;

(3) Better fruit quality is expected for treatments where lower pesticide application rates or concentrations are used. The physiological characteristics of the fruit are expected to be 10-20% better in treatments with reduced spray concentrations and spray volumes.

(4) Technical factors of spray application play an important role in the deposition and drift of sprays. Nozzles that produce a smaller droplet spectrum achieve greater coverage of the treated area and better control of pests (30-40%). In addition, the use of ITR nozzles with air injection is expected to reduce drift by 20-40 % with the same deposition compared to a standard ITR nozzle;

(5) The influence of the growing season on the results of the main research properties is expected (15-25%).

4. Conclusion

The aim of the research is to obtain empirical results in field research on the effectiveness of various factors influencing the complex process of plant protection. This topic has never been studied in the Republic of Croatia in a multidisciplinary agronomic approach, in which various knowledge from the fields of agricultural engineering (mechanization), production technology and plant protection in the narrower sense should be complemented and combined. It has already been established that the plant protection process is extremely complex, whereby only one of the application factors can have a positive or negative effect on the effectiveness of the spraying and the residues of the pesticide active substance. However, some of the most important factors that have a greater influence on the effectiveness of plant protection should be listed: the type of machine (sprayer) at application; the type of nozzles at application; the concentration of the spray; the spraying rate; pesticide grace period; the number of applications during the growing season; the physical and chemical properties of the spray; the agricultural crop in the study; the weather conditions at direct application; the weather conditions during the growing season between years; the pest biology; the deposition of the spray; the drift of the spray.

The complexity of factors in the plant protection process is evident from the above list and this project proposal and field research will cover most of these factors. The aim of the project proposal is therefore to investigate the interdependence of the main characteristics of crop protection on spray efficacy, pesticides residues in fruit, fruit quality, pest control and pest incidence, and spray deposition and drift, i.e. to apply the principles of using the technology of reduced dosage and concentration of pesticide active ingredients (low volume pesticide management) – FAO 2022.

The main objectives of this project proposal relate to the proposed field research under real time conditions (Real Time Research):

- Determination of the influence of technology (agricultural machinery with different types of nozzles) on: Pesticide residues in the fruits of permanent crops; occurrence and development of pests during the growing season, fruit characteristics (morphological, pomological, physiological and economic) and spray deposition and drift;
- Determination of the influence of the protection technology in permanent crops (reduced spraying volumes and reduced spray concentrations) on: Pesticide residues in fruits of permanent crops; occurrence and development of pests during the growing season, fruit characteristics (morphological, pomological, physiological and economic) and spray deposition and drift;
- Determination of the influence of the vegetation period on the above-mentioned characteristics;
- To gain insights into the possibility of reducing the standard and dosage of sprays (low pesticide management) with the same or better biological effect on pests and lower pesticide residues in fruit over two years in two permanent plantations.

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ANALYTICAL SOLUTION OF CONVECTIVE DRYING OF THIN APPLE SLICES WITH MICROWAVE PRE-TREATMENT

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Abstract. The aim of this study was to experimentally investigate the drying characteristics of Idared apple thin discs (slices) during convective drying with microwave (MW) pre-treatment and to develop analytical modeling for thin-layer convective drying of apple slices. The drying experiments were carried out in laboratory-scale hot-air dryer using apple discs of 2 mm thickness at a drying temperature of 50 °C. The air velocity during all experiments was maintained at 2 m/s. MW pre-treatments were applied in a microwave oven operating at 700 W, with exposure times of 1 min, and 3 min. For each experiment, the drying time and equilibrium moisture content were determined. Analysis of drying curves showed that MW pre-treatment significantly reduced the overall drying time.

Keywords: apple slices, convective drying, MW, analytical solution

1. Introduction

Drying is one of the principal unit operations in food and postharvest processing, employed to reduce moisture content, inhibit microbial growth, and extend shelf life [1], [2]. In thin-layer drying of fruit slices such as apples, controlling drying kinetics while preserving product quality is a persistent challenge. Convective hot air drying remains widely used owing to its simplicity and scalability, but its slow rates and potential quality degradation increase interest in pre-treatments that accelerate moisture removal [3].

Microwave pre-treatment is a promising approach, because microwave energy penetrates the sample, generating internal heating and vapor pressure that can enhance moisture diffusive fluxes [2]. Several studies report that combining convective drying with microwave or microwave-assisted steps reduces drying time significantly compared to convection alone [1], [2], [3], [4]. In apple slices, for example, microwave-vacuum pre-treatments have been shown to reduce drying time by 25–45% versus untreated slices [5], [6]. However, the application of microwaves may also accelerate undesirable changes (e.g. surface hardening, quality deterioration) unless well integrated into a modeling framework that accounts for evolving transport properties.

Mechanistic modeling of drying processes is crucial for predictive design, process optimization, and scale-up. Classical approaches treat drying as unsteady diffusion through the material, often applying Fick's second law with convective boundary conditions [7]. In fruit drying, effective moisture diffusivity (D_{eff}) and surface mass transfer coefficient (k_c) are key parameters, typically estimated by fitting models to experimental moisture ratio (MR) data [8]. While many models assume constant diffusivity, recent work suggests that transport properties may evolve due to structural changes (e.g. porosity variation, shrinkage) during drying [9], [10]. Time-dependent or moisture-dependent parameter formulations can better capture such dynamics but at the cost of additional complexity and potential parameter identifiability issues [11], [12], [13].

In this study, we focus on thin discs (2 mm) of *Idared* apple variety subjected to convective drying at 50 °C, with or without microwave pre-treatment (1 min, and 3 min exposure). Our aims are twofold: (i) to experimentally characterize and compare drying kinetics under the different pre-treatment regimes, and (ii) to develop and validate an analytical modeling framework that uses a constant D_{eff} paired with a time-varying kc, thus balancing economy and mechanistic interpretability. The resulting model can help elucidate the role of internal diffusion versus surface resistance in thin fruit slices and guide the design of efficient drying protocols.

2. Theory

2.1. Analytical solution of moisture diffusion in slab geometry

Drying of biological products is primarily governed by unsteady-state moisture transport, which is often described by *Fick's second law of diffusion* [7]. For apple slices where the thickness (L) is much smaller that the radius (L≪R), the geometry can be approximated as a *thin disk*. In this case, axial diffusion across the thickness dominates, whereas radial diffusion can be neglected.

For isotropic and homogeneous media, the one-dimensional (1-D) diffusion equation is expressed as,

$$\frac{\partial \mathbf{M}}{\partial \mathbf{t}} = D_{eff}\frac{\partial^2 M}{\partial x^2}, \qquad 0 \le x \le L \tag{1}$$

where D_{eff} is the effective moisture diffusivity, (m^2/s), M is the local moisture content (kg_w/kg_{dm}) at position x and time t, and x is the distance from the mid-plane (0 at the center, L at the surface). The initial condition assumes a uniform moisture distribution, $M(x, 0)=M_0$. At the surfaces, convective mass transfer to air is described by a *Robin*-type boundary condition:

$$-D_{eff}\frac{\partial M}{\partial x}\Big|_{x=L} = k_c(M_s - M_\infty). \tag{2}$$

where kc is the convective mass transfer coefficient (m/s), Ms is the surface moisture content, and M_∞ is the equilibrium value. Symmetry is imposed at the mid-plane, ($\partial M/\partial x\,|_{x=0} = 0$). In this formulation, the moisture flux boundary condition is applied to both flat faces of the slab. For long drying times or small Biot numbers, the analytical solution for a plane slab [7] simplifies to:

$$\mathbf{MR} \approx \frac{\mathbf{8}}{\pi^2} exp\left(-\frac{\pi^2 D_{eff}\,\mathbf{t}}{\mathbf{4L^2}}\right) \tag{3}$$

This first-term approximation is valid when $t > 0.2L^2/D_{eff}$, as higher-order terms decay exponentially faster. The average moisture content can be obtained by integration across the slab thickness, $M(t) = \frac{1}{L}\int_0^L M(x,t)dx$. In practice, model fitting to experimental moisture data is performed by nonlinear regression, simultaneously estimating D_{eff} and k_c. The quality of the model fit is evaluated using root mean square error (RMSE) and the adjusted coefficient of determination R^2_{adj}.

2.2 Justification of the slab geometry assumption (axial vs. radial diffusion, Biot numbers)

The dominance of axial diffusion in apple slices can be demonstrated by comparing characteristic surface areas and diffusion times. The total area of the two flat faces is $A_{faces} \approx 2\pi R^2$, whereas the curved side area is $A_{side} \approx 2\pi RL$. For a 2 mm-thick slice with initial radius of 0.0375 m, the side area accounts for only about 5% of the total surface, indicating that most moisture transfer occurs through the faces. Characteristic diffusion times are defined as $\tau z = D_{eff}\ tf\ /\ L^2$ and $\tau_r = D_{eff}\ t_f\ /\ R^2$ with $D_{eff} \approx 10^{-6}$ m²/s, L=0.001 m, and $t_f \approx 13{,}000$s, the axial diffusion time ($\tau_z \approx 10$) indicates essentially complete moisture equilibration across the thickness, whereas radial diffusion ($\tau_r \approx 10^{-2}$) is negligible. Thus, moisture gradients across the thickness dominate, validating the use of the slab (1-D axial) model for drying of apple slices.

2.3 Internal vs. external resistances and Biot number

The relative importance of internal and external resistances is quantified by the Biot number defined as $Bi = kc\ L/D_{eff}$. When $Bi \gg 1$, internal diffusion dominates; when $Bi \ll 1$, external mass transfer dominates. For apple slices dried at 50 °C, estimated Biot numbers are very small (10^{-4} - 10^{-3}), confirming that internal diffusion is the rate-limiting step, whereas surface resistance plays only a minor role. This theoretical framework underpins the modeling approach used in this work, where D_{eff} represents the internal diffusion process and k_c captures external resistance effects, which may vary with drying time due to evolving surface structure microstructure.

3. Materials and Methods

3.1 Preparation of apple slices

Fresh Idared apples were used in all experiments. The apples were washed with tap water, before being cut into thin circular slices. The initial geometry of the slices was as follows: thickness (2L)=0.002 m (L=0.001 m, representing the half-thickness used in modeling). The average initial diameter was 0.075m (corresponding to an initial radius R≈0.0375 m), which gradually decreased to approximately 0.055 m after drying (average R≈0.0275 m). These dimensions were used in the calculation of effective surface area and characteristic diffusion times. The mass of the samples was 86.48 g, 65.51 g, and 76.22 g for convective, 1 min and 3 min convective drying with microwave pre-treatment, respectively. The precision balance used in the experiments was KERN & Sohn, KB 3600-2N with the accuracy of ±0.01 g. The experiments were done only once. The ambient relative humidity was not controlled or recorded, but it was measured with digital hygrometer and it was between 55-60% during the experiments.

3.2 Drying experiments

Convective drying was carried out in a laboratory-scale hot air dryer operating at 50 °C and an air velocity of 2 m/s. Eight apple slices for each experiment were placed on a perforated tray to ensure uniform exposure to the drying air. Microwave (MW) pre-treatments were applied prior to hot air drying to assess their effect on drying kinetics. A domestic microwave oven (maximum output power 700 W) was used, with exposure times of 1 min and 3 min. The MW pre-treatments with 700 W of power for 1 min, and 3 min were chosen because by the test experiments it was concluded that this power output and exposure time are the most suitable for the samples' mass, since MW energy absorption strongly depends on thickness and load. Immediately after the MW treatment, the slices were transferred to the hot-air dryer and dried under the same conditions as the untreated samples. The moisture content of apple slices (kg_w/kg_{dm}) was determined gravimetrically at regular time intervals during drying. The moisture ratio (MR) was calculated using the following expression $MR(t) = {M_t - M_{eq}}/{M_0 - M_{eq}}$, where M_t is the moisture content at time t, M_0 is the initial moisture content, and M_{eq} is the equilibrium moisture content.

3.3 Numerical modeling of moisture diffusion

Drying kinetics was simulated as one-dimensional moisture diffusion across the slice thickness, based on Fick's second law with Robin-type boundary conditions (see Section 2). The following assumptions were applied:

- Moisture transport occurred only in the axial direction, justified by the condition L≪R.
- Shrinkage was considered negligible in thickness but accounted for in diameter.
- The equilibrium moisture content was determined experimentally for each drying condition.

3.3.1 Crank–Nicolson scheme

The partial differential equation was solved using the *Crank–Nicolson finite difference* method, which is second-order accurate in space and time, and is unconditionally stable. The slab half-thickness was discretized with 150 spatial nodes, and symmetry was imposed at the mid-plane. The *Robin* boundary condition applied at the slab surface allowed simultaneous modeling of internal diffusion (described by D_{eff}) and external convection (characterized by k_c) defined in Equation (2). Figure 1 presents the workflow for numerical modeling of drying curves, including data input, Crank–Nicolson solver, fitting procedure, and post-processing.

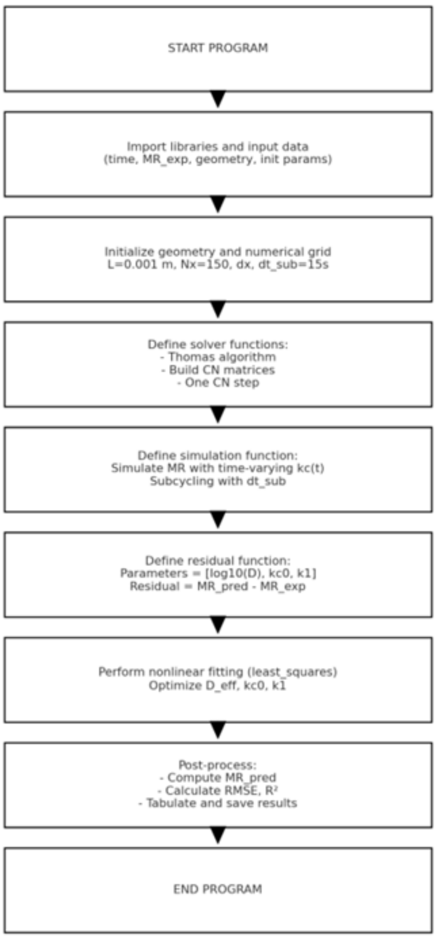

Figure 1. Workflow for numerical modeling of drying curves, including data input, Crank–Nicolson solver, fitting procedure, and post-processing.

3.3.2 Parameter estimation

The effective diffusivity (D_{eff}) was assumed constant, while the surface mass transfer coefficient (k_c) was allowed to vary with time to account for evolving surface characteristics (e.g., pore formation, microstructural collapse). A linear time-dependent expression was used: $k_c(t)=k_{c0}+k_1(t/t_{max})$ where k_{c0} is the initial surface coefficient, k_1 is the rate of change, and t_{max} is the total drying time. The time-averaged surface coefficient over the drying period is given by:

$$\bar{k}_c = \frac{1}{t_{max}} \int_0^{t_{max}} k_c(t)\,dt = k_{c0} + \frac{k_1}{2} \quad (4)$$

The model was fitted to the experimental MR data using nonlinear least-squares regression, treating D_{eff}, k_{c0}, k_1 as adjustable parameters [13]. The quality of the fit was evaluated using the root mean square error (RMSE) and the adjusted coefficient of determination (R^2_{adj}).

4. Results and Discussion

4.1. Air drying of apple slices at 50 °C

The drying behavior of untreated apple slices was accurately simulated using the 1-D diffusion model with a time-varying surface mass transfer coefficient (k_c). The model was fitted to the experimental moisture ratio (MR) data by nonlinear least squares regression, with D_{eff}, k_{c0} and k1 as free parameters, while the initial and equilibrium moisture contents (M_0=7.34 kg_w/kg_{dm}, M_{eq}=0.20 kg_w/kg_{dm}) were fixed.

The optimized parameters were $D_{eff}=9.74\times10^{-7}\,m^2/s$, $k_{c0}=1.20\times10^{-7}\,m/s$, and $k_1=5.76\times10^{-7}\,m/s$ (Table 1). The model showed excellent agreement (Figure 2) with the experimental data (R^2_{adj}=0.996, RMSE=0.0198).

Table 1. Drying simulation parameters

Drying Case	$D_{eff}\times10^{-7}$ (m^2/s)	$k_{c0}\times10^{-7}$ (m/s)	$k_1\times10^{-7}$ (m/s)	Bi, avg $\times10^{-4}$	$Bi_0\times10^{-4}$	$Bi_f\times10^{-4}$	RMSE	R^2_{adj}	Interpretation
Air drying 50 °C	9.74	1.20	5.75	4.19	1.23	7.14	0.0187	0.996	Diffusion-controlled, kc increases slightly
Microwave (1 min-700W) and air drying at 50 °C	9.99	1.88	5.38	4.57	1.88	7.26	0.0115	0.998	Faster drying, moderate kc increase

Microwave (1 min-700W+2 min-140W) and air drying at 50 °C	10.0	1.94	7.02	5.45	1.94	8.96	0.0119	0.998	Stronger kc increase, still diffusion-controlled

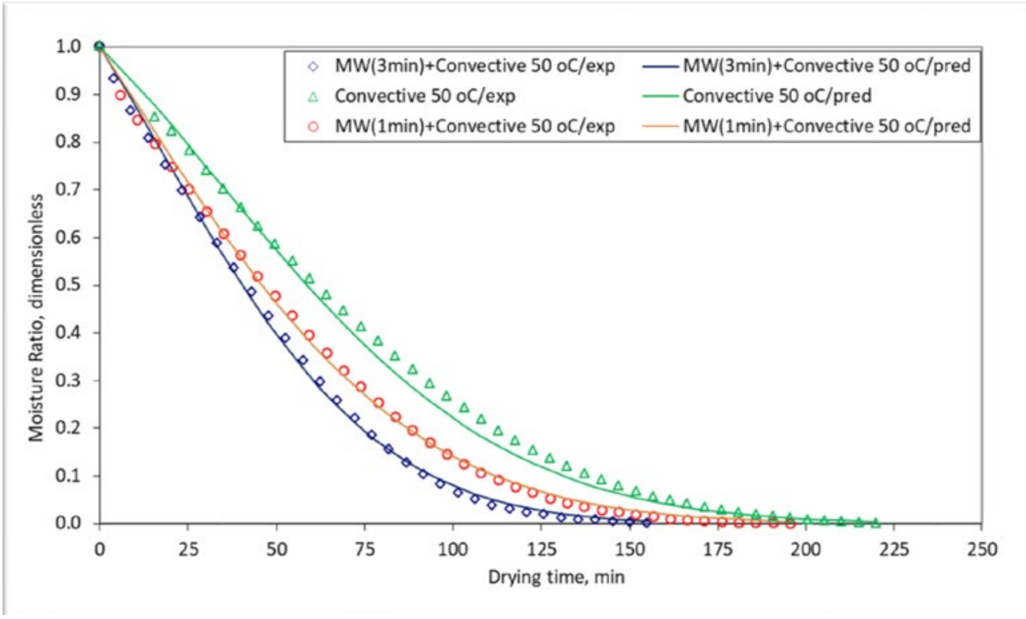

Figure 2. Experimental and simulated drying curves of apple slices: (a) hot-air drying at 50 °C, (b) microwave pre-treatment (1 min) + hot air drying, (c) microwave pre-treatment (3 min) + hot air drying. Symbols represent experimental data; solid lines represent model predictions using constant D_{eff} and time-varying k_c.

The Biot numbers for mass transfer in the slab model ranged between 1.23×10^{-4} (initial) and 7.14×10^{-4} (final) with an average $\bar{Bi}=4.19\times10^{-4}$ (Table 1). These small Biot numbers confirm that moisture transfer was predominantly controlled by internal diffusion within the apple tissue rather than by external convective resistance. Although kc increased during drying, the Biot numbers remained well below unity ($\ll$1), reinforcing that the surface resistance played only a minor role.

Reported Biot numbers for fruit and vegetable drying typically range between 10^{-3} and 10^{-1}, depending on product structure, air velocity, and geometry [14]. The estimated diffusivity aligns with literature values for apple tissues dried at moderate temperatures, typically in the range 0.5×10^{-6}–2×10^{-6} m²/s [14].

4.2. Effect of microwave pre-treatment (1 min)

Microwave pre-treatment (700 W for 1 min) reduced the initial moisture content from 7.34 kg_w/kg_{dm} to M_0=6.65 kg_w/kg_{dm}. The sample diameter decreased slightly during dehydration (initial radius R=0.0375 m, final R=0.0365 m). Moisture ratio data were collected at 41 time points up to 11,742 s. The overall drying caused only limited radial shrinkage (<7%), which supports the earlier assumption that L≪R and τz>>τr.

The optimized parameters were $D_{eff}=9.99\times10^{-7}$ m^2/s, $k_{c0}=1.88\times10^{-7}$ m/s, and $k_1=5.38\times10^{-7}$ m/s. The surface mass transfer coefficient increased from 1.88×10^{-7} m/s to 7.26×10^{-7} m/s during drying (Table 1). The model closely reproduced the experimental drying curve (R^2_{adj}=0.998 and RMSE=0.0115), confirming its accuracy across both the early and late stages of drying (Figure 2).

The Biot number was calculated at different stages of drying. It increased from 1.88×10^{-4} (initial) to 7.26×10^{-4} (final), with an average of 4.57×10^{-4}. These low values confirm that drying remained diffusion-controlled, dominated by internal moisture movement rather than by external resistance.

The improvement in drying kinetics compared with untreated slices can be attributed to MW-induced microstructural changes that enhanced surface permeability—consistent with microscopy observations of increased porosity in pre-treated fruits [4], [8]. The Biot numbers observed here are at the low end of typical ranges for fruits and vegetables (10^{-3}–10^{-1}), which is consistent with the thin geometry and high diffusivity of apple slices at 50 °C.

4.3 Microwave pre-treatment (3 min)

Sequential microwave pre-treatment at 700 W for 1 min followed by 140 W for 2 min further reduced the initial moisture content to 4.43 kg_w/kg_{dm} The slice diameter decreased slightly during drying (initial radius R=0.0375 m and final R=0.0325 m).

The surface mass transfer coefficient k_c increased steadily during drying, reflecting progressive changes in the product surface. It increased from 1.94×10^{-7} m/s to 8.96×10^{-7} m/s, with an average of 5.45×10^{-7} m/s. These magnitudes are consistent with reported values for apple slices (10^{-7}—10^{-6} m/s), depending on air velocity and sample geometry [8], [14]. The model provided an excellent description of the experimental drying curves (RMSE=0.0119 and R^2_{adj}=0.998) seen in Figure 2.

The monotonic increase in kc with time can be attributed to microstructural phenomena such as cuticle breakdown, pore formation, and surface roughening (case hardening), which collectively reduce external resistance to vapor escape as dehydration progresses. This interpretation agrees with previous microscopy observations of apple tissue showing a more porous surface structure as drying advances.

By contrast, D_{eff} could be adequately represented by a constant value ($\approx1.0\times10^{-6}$ m^2/s). This estimate lies within the range reported for apple and similar fruit tissues at 50 °C (5×10^{-7}-2×10^{-6} m^2/s) [8], [14]. Although some studies employ moisture-dependent D_{eff} formulations that decrease exponentially with decreasing moisture ratio (MR), the present results demonstrate that, for thin apple slices with limited shrinkage, a constant

Deff combined with a time-dependent kc is adequately reproduces drying kinetics with high accuracy. This finding suggests that surface evolution, rather internal structural change, primarily governs the observed improvement in model accuracy [12].

Biot number calculations further supports this conclusion. Across all cases, Biot numbers remained low, ranging from 1.94×10^{-4} initially to 8.96×10^{-4} at the end of drying (average$\approx5.45\times10^{-4}$). These values, one to two orders of magnitude below unity, indicate that drying was diffusion-controlled, with negligible external resistance. Similar results were reported by [8], who found that thin fruit and vegetable slices exhibit Biot < 0.01, while thicker products such as banana slices can reach Biot ≈ 0.1, indicating greater convective limitation.

Microwave pre-treatment thus accelerated drying primarily by lowering the initial moisture and enhancing surface permeability, without significantly altering D_{eff} [6]. The consistently low Biot numbers ($\approx10^{-4}$) confirm that drying of thin apple slices at 50 °C is governed predominantly by internal moisture diffusion.

The choice between time-dependent and moisture-dependent formulations of transport parameters warrants further consideration. The time-varying kc approach used here is empirical but provides a realistic way to simulate evolving surface conditions without over-parameterizing the model. In contrast, moisture-dependent diffusivity models are more mechanistic, linking transport resistance to the internal water state. However, they require additional assumptions and may introduce parameter non-uniqueness.

Given the nearly exponential drying curves, the limited radial shrinkage (0.0375 m $\rightarrow$ 0.0275 m), and the very low Biot numbers, the simpler formulation with constant Deff and time-varying kc is fully justified. For products with greater structural collapse, such as tomatoes or bananas, moisture-dependent diffusivity models may be necessary to maintain predictive accuracy.

In summary, the present analysis demonstrates that convective air drying of apple slices at 50 °C is predominantly governed by internal diffusion, with external resistance decreasing as surface properties evolve. The combination of constant effective diffusivity and time-dependent surface mass transfer coefficient yielded excellent predictive accuracy and physically interpretable results. These findings are in close agreement with international literature and highlight the importance of tailoring diffusion models to the geometry and microstructural behavior of the product under study. The MW pre-treatment reduced drying time at 50 °C, by 12% (700 W for 1 min) and 42% (MW combined treatment for 3 min) relative to untreated slices.

5. Conclusions

This study investigated the convective drying of thin Idared apple slices with and without microwave (MW) pre-treatment, combining experimental data with analytical modeling. A one-dimensional diffusion model with constant effective diffusivity (Deff) and time-varying surface mass transfer coefficient (k_c) accurately described the drying behavior of apple slices under all tested conditions ($R^2_{adj}>0.996$). The estimated Biot numbers (10^{-4}—10^{-3}) confirmed that drying of thin apple slices at 50 °C was governed primarily by internal diffusion, with surface resistance contributing only marginally. The effective moisture diffusivity (D_{eff}) was consistently around 1.0×10^{-6} m^2/s, in good agreement with literature for apple tissues. The surface mass transfer coefficient (k_c) increased progressively during drying, from approximately 2.0×10^{-7} to 9.0×10^{-7} m/s), reflecting structural modifications at the slice surface. Microwave pre-treatment reduced the initial moisture content and accelerated drying rates, mainly by improving surface permeability. Also, MW pre-treatment reduced drying time at 50 °C, by 12% (700 W for 1 min) and 42% (MW combined treatment for 3 min) relative to untreated slices. However, it did not significantly alter the internal diffusivity of the apple tissue. For thin fruit slices, modeling with constant D_{eff} and time-dependent k_c provides both predictive accuracy and physical interpretability. MW pre-treatment is an effective means of reducing drying time, but the overall drying kinetics remain diffusion-controlled, governed by internal moisture transport.

NOMENCLATURE

Symbol	Definition	Units
M	moisture content (db)	$kg_{water}/kg_{dry\ matter}$
M_0	initial moisture content (db)	$kg_{water}/kg_{dry\ matter}$
M_{eq}	equilibrium moisture content (db)	$kg_{water}/kg_{dry\ matter}$
MR	moisture ratio $(M-Me_q)/(M_0-M_{eq})$	dimensionless
t	drying time	s
t_{max}	total drying time	s
L	half-thickness of the apple slice (slab model)	m
R	slice radius (initial or final, depending on shrinkage)	m
k_c	mass transfer coefficient at the product–air interface	m/s
k_{c0}	initial surface mass transfer coefficient	m/s
k_1	linear coefficient for time-varying surface transfer	m/s
D_{eff}	effective water diffusivity	m^2/s
Bi	Biot number, $k_c\ L/D_{eff}$	dimensionless
Bi_0	initial Biot number at t=0	dimensionless
Bi_f	final Biot number at $t=t_{max}$	dimensionless
$\overline{Bi}$	average Biot number (over drying period)	dimensionless
τz	characteristic drying time in thickness direction	s
τr	characteristic drying time in radial direction	s
RMSE	root mean square error (experimental-predicted MR)	dimensionless
R^2_{adj}	adjusted coefficient of determination	dimensionless

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Supplement

1. Full numerical Crank–Nicolson fit with time-varying kc written in Python

```
# New drying case (Meq = 0): 1-D slab CN with time-varying kc(t) = kc0 + k1 * t
/ t_final
# Geometry: thickness = 0.002 m -> L = 0.001 m. Radius shrink 0.0325 -> 0.0275
m (ignored in 1-D z model).
# Fit parameters: D_eff, kc0, k1. Return full table (4 decimals) and metrics.

import numpy as np, pandas as pd, time
from scipy.optimize import least_squares
from caas_jupyter_tools import display_dataframe_to_user

start = time.time()

# Experimental MR data
t_data = np.array ([0,240,532,824,1117,1409,1701,1993,2285,2577,2870,3162,3454,
3746,4039,4331,4623,4915,5207,5499,5792,6084,6376,6669,6961,7253,7545,7837,8129,84
22,8714,9006,9298], dtype=float)
MR_exp=np.array ([1.0,0.931793478,0.865217391,0.807336957,0.750543478,0.695923
913,0.641304348,0.5875,0.533695652, 0.483695652,0.433152174,0.386413043,0.34076087,0
.296467391,0.256793478,0.218478261,0.183423913,0.153532609,0.125543478,0.102445652,
0.080706522,0.063586957,0.050543478,0.0375,0.02826087,0.021467391,0.017119565,0.011
413043,0.007608696,0.005978261,0.002445652,0.001902174,0.0], dtype=float)

# Geometry / numerics
L = 0.001  # half-thickness
Nx = 150
dx = L / Nx
dt_sub = 12.0  # smaller substep for accuracy
weights = np.ones(Nx+1); weights[0]=0.5; weights[-1]=0.5; weights = weights / Nx
t_final = t_data[-1]
```

```
# Thomas solver
def solve_tridiagonal(a,b,c,d):
    n=len(b)
    cp=np.empty(n-1); dp=np.empty(n)
    cp[0]=c[0]/b[0]; dp[0]=d[0]/b[0]
    for i in range(1,n-1):
        denom=b[i]-a[i-1]*cp[i-1]
        cp[i]=c[i]/denom
        dp[i]=(d[i]-a[i-1]*dp[i-1])/denom
    dp[n-1]=(d[n-1]-a[n-2]*dp[n-2])/(b[n-1]-a[n-2]*cp[n-2])
    x=np.empty(n); x[-1]=dp[-1]
    for i in range(n-2,-1,-1):
        x[i]=dp[i]-cp[i]*x[i+1]
    return x

def build_ops(D, kc):
    n=Nx+1
    lower=np.zeros(n-1); diag=np.zeros(n); upper=np.zeros(n-1)
    invdx2 = 1.0/(dx*dx)
    for i in range(1,n-1):
        lower[i-1]=D*invdx2
        diag[i]=-2*D*invdx2
        upper[i]=D*invdx2
    diag[0]=-2*D*invdx2; upper[0]=2*D*invdx2
    lower[-1]=2*D*invdx2
    diag[-1]=-2*D*invdx2 - 2*kc/dx
    return lower,diag,upper

def cn_step(C_old, D, kc, dt):
    lower,diag,upper=build_ops(D,kc)
    n=Nx+1
    aM = -0.5*dt*lower.copy()
    bM = 1.0 - 0.5*dt*diag
    cM = -0.5*dt*upper.copy()
    rhs = np.zeros(n)
    rhs[0] = (1.0 + 0.5*dt*diag[0])*C_old[0] + 0.5*dt*upper[0]*C_old[1]
    for i in range(1,n-1):
            rhs[i] = 0.5*dt*lower[i-1]*C_old[i-1] + (1.0 + 0.5*dt*diag[i])*C_old[i] +
0.5*dt*upper[i]*C_old[i+1]
    rhs[-1] = 0.5*dt*lower[-1]*C_old[-2] + (1.0 + 0.5*dt*diag[-1])*C_old[-1]
    C_new = solve_tridiagonal(aM,bM,cM,rhs)
    return C_new
```

```
# simulate with kc(t) = kc0 + k1 * t / t_final (Meq=0, MR = mean(C))
def simulate_timevary_kc(D, kc0, k1):
    C = np.ones(Nx+1)
    MR_model = []
    t_prev = 0.0
    for t_target in t_data:
        dt_total = t_target - t_prev
        if dt_total <= 0:
            MR_model.append(np.dot(weights, C)); continue
        remaining = dt_total
        while remaining > 1e-12:
            dt = min(dt_sub, remaining)
            t_mid = t_prev + 0.5*dt
            kc_now = kc0 + k1 * (t_mid / t_final)
            kc_now = max(kc_now, 1e-12)
            C = cn_step(C, D, kc_now, dt)
            C = np.maximum(C, 0.0)
            t_prev += dt
            remaining -= dt
        MR_model.append(np.dot(weights, C))
    return np.array(MR_model)

# residuals: x = [log10(D), kc0, k1]
def residuals_timevary(x):
    logD, kc0, k1 = x
    D = 10**logD
    pred = simulate_timevary_kc(D, kc0, k1)
    return pred - MR_exp

# initial guess and bounds
x0 = [np.log10(2.0e-8), 2.0e-7, 0.0]
lb = [np.log10(1e-12), 1e-10, -5e-6]
ub = [np.log10(1e-6), 1e-3,  5e-6]

res = least_squares(residuals_timevary, x0, bounds=(lb,ub), xtol=1e-9, ftol=1e-9,
gtol=1e-9, max_nfev=300)

logD_opt, kc0_opt, k1_opt = res.x
D_opt = 10**logD_opt
MR_pred = simulate_timevary_kc(D_opt, kc0_opt, k1_opt)

# metrics
diff = MR_exp - MR_pred
```

```
RMSE = np.sqrt(np.mean(diff**2))
MAE = np.mean(np.abs(diff))
ss_res = np.sum(diff**2)
ss_tot = np.sum((MR_exp - np.mean(MR_exp))**2)
R2 = 1 - ss_res/ss_tot
npts = len(MR_exp); p = 3
R2_adj = 1 - (1 - R2) * (npts - 1) / (npts - p - 1)

# Table rounded
df = pd.DataFrame({'Time_s': t_data, 'MR_exp': np.round(MR_exp,4), 'MR_pred': np.round(MR_pred,4)})
display_dataframe_to_user("Case 3: MR_exp vs MR_pred (time-varying kc, Meq=0)", df)

print("Fit complete (time-varying kc, Meq=0).")
print(f"D_eff = {D_opt:.6e} m^2/s")
print(f"kc0   = {kc0_opt:.6e} m/s")
print(f"k1    = {k1_opt:.6e} m/s (over t_final scale)")
print("Metrics:")
print(f" RMSE = {RMSE:.6g}, MAE = {MAE:.6g}, R2 = {R2:.6g}, R2_adj = {R2_adj:.6g}")
print("Elapsed: {:.1f} s".format(time.time()-start))
```

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REGULATORY CHALLENGES AND FRAMEWORKS FOR UAV-BASED CHEMICAL APPLICATIONS IN AGRICULTURE

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Abstract. Unmanned aerial vehicle (UAV) systems for chemical crop protection have experienced significant global growth. They offer precise, efficient, and targeted pesticide application as part of precision agriculture. However, the rapid technological advancement of UAV spraying systems has not been matched by equally fast regulatory development. This has resulted in fragmented frameworks, legal uncertainties, and barriers to widespread adoption. This paper reviews international and national regulations governing UAV-based spraying, with a particular focus on the United States, the European Union, Asia, and Serbia. Special attention is given to differences within the EU. For example, countries such as Hungary and Switzerland have introduced national authorizations for UAV spraying, while others remain limited by general pesticide-use rules. In Serbia, the absence of UAV-specific legislation and the lack of registered pesticides approved for use with UAVs represent critical constraints. This is occurring despite increasing farmer interest and positive field research results. The analysis highlights four key regulatory challenges: safety, environmental protection, equipment certification, and operator training. It also identifies the absence of UAV-specific pesticide registration as a major obstacle to adoption. The study concludes with recommendations to harmonize aviation and plant protection regulations, develop UAV-specific product registration pathways, and adopt international standards. These steps aim to ensure safe, sustainable, and legally secure integration of UAV systems in chemical crop protection.

Keywords: UAV SYSTEMS, PESTICIDES, STANDARDS, REGULATIONS, OPERATOR TRAINING

1. Introduction

Modern agriculture is working to achieve a delicate balance between two critical objectives: ensuring an adequate food supply while safeguarding the environment. A significant aspect of this challenge involves the responsible use of pesticides, ensuring that each application is effective. In this regard, unmanned aerial vehicles (UAVs) have emerged as a valuable asset in precision agriculture [1]. These UAVs enable farmers to target only the areas of the field that require treatment, often resulting in reduced chemical usage without compromising effectiveness. Additionally, UAVs allow operators to maintain a safe distance from the spraying process [2]. They are particularly advantageous for rapid responses to pest or disease outbreaks and can access challenging terrains where traditional machinery may struggle, such as steep slopes, small plots, or regions near water bodies.

Asia has witnessed a significant surge in the commercial use of unmanned aerial vehicle (UAV) systems, with Japan pioneering their agricultural application as early as the 1990s [3]. China has since emerged as a leader, boasting both the largest fleet of UAVs and the most extensive area treated using this technology [4]. While the United States and the European Union have also adopted UAVs in agriculture, regulatory hurdles have somewhat restricted their widespread implementation [5, 6]. Serbia, too, is experiencing a growing interest in this field. Reports indicate that by the start of 2025, UAV usage is on the rise, accompanied by increasing [7]. This growth is often fueled by local distributors promoting advanced models such as the DJI Agras T50 and EAVision J100 [2].

The rapid advancement of UAV technology has left the laws governing it struggling to keep up. As unmanned aerial vehicles (UAVs) become more sophisticated, the rules and regulations surrounding their use are a patchwork of different approaches and often out of date [5]. Countries have their own specific rules about how high UAVs can fly, what kind of equipment they need to have, how pilots should be trained, and even how they can be used to spray pesticides [10]. This lack of consistency makes it harder to fully utilize the potential of this technology and creates legal confusion for both the companies that make UAVs and the people who use them. Beyond safety, environmental protection is a major concern. Any use of UAVs for spraying pesticides must follow strict rules to protect water, soil, and other living things [11]. Another hurdle is the need for standardized equipment and application methods. Although international groups like ISO and national standards organizations are working on guidelines for UAVs, these are not yet widely used in practice.

Serbia's agricultural use of UAVs for crop protection is just beginning. Current rules mostly lean on general aviation and pesticide guidelines, with little specific regulation for UAV chemical spraying. This situation calls for a deep dive into international standards and a comparison to find ways to safely and sustainably integrate UAV technology into Serbian farming.

The aim of this paper is to provide an overview of international and national regulatory frameworks related to the use of UAV systems in chemical crop protection. Special emphasis is placed on regulations in the United States, the European Union, Asia, and Serbia. In addition to reviewing existing provisions, the paper identifies key challenges, safety, environmental protection, equipment certification, and operator training, and offers recommendations for improving legislation in order to foster broader and more responsible adoption of UAV systems in agriculture.

2. International Regulatory Frameworks for UAV-Based Applications

The integration of UAV-based spraying systems into agriculture has been addressed differently across global regions, reflecting variations in legislative maturity, institutional capacity, and adoption rates (Table 1) [2]. While Asia has pioneered the commercial use of UAVs in crop protection, the United States and the European Union have adopted more cautious and highly regulated approaches, often prioritizing airspace safety and environmental protection [12]. Overall, the regulatory framework for UAV systems for chemical crop protection remains highly fragmented. Although UAV spraying technologies have advanced rapidly and demonstrated clear agronomic benefits, legislation has lagged behind, creating legal uncertainties and barriers to broader adoption. Regulatory challenges generally concentrate on four pillars (Figure 1).

Figure 1. Main regulatory challenges related to UAV operations in crop protection.

Nevertheless, national frameworks differ considerably in their scope and enforcement, resulting in diverse implications for the practical deployment of UAV-based chemical application systems [7].

Asia

Asia represents the most dynamic region for UAV adoption in agriculture. Japan, as an early adopter, has deployed UAV spraying since the 1990s, with strong institutional support from the Ministry of Agriculture, Forestry and Fisheries (MAFF). The Yamaha RMAX model became one of the first certified UAV sprayers, marking a milestone in agricultural aviation regulation [4]. China, on the other hand, has rapidly scaled up UAV adoption, supported by subsidies, pilot training programs, and policies under the Ministry of Agriculture and Rural Affairs (MARA). China now leads globally in both UAV fleet size and treated farmland area [5]. Despite these successes, challenges remain regarding operator licensing, standardization of spraying techniques, and environmental safeguards.

United States

In the United States, UAV operations are governed by the Federal Aviation Administration (FAA), with the core regulatory framework outlined in Part 107 of the Federal Aviation Regulations [5]. This legislation establishes requirements for pilot certification, aircraft registration, and operational limitations such as altitude, line-of-sight operation, and flight over people. However, the agricultural use of UAVs for pesticide application requires additional approval under the Federal Insecticide, Fungicide, and Rodenticide Act (FIFRA) and relevant state-level pesticide laws. Recent initiatives by the FAA and the Environmental Protection Agency (EPA) highlight the need for harmonization between aviation safety and environmental regulations [1,2]. Despite progress, fragmented jurisdiction and a lengthy exemption process remain key barriers to large-scale deployment.

European Union

The European Union has developed a harmonized regulatory framework through the European Union Aviation Safety Agency (EASA), which since 2021 enforces unified UAV regulations across member states [10]. These rules categorize UAV operations into open, specific, and certified categories, depending on risk level. Agricultural UAV spraying generally falls under the specific category, requiring operational risk assessments (SORA) and authorization from national aviation authorities [10].

In parallel, UAV pesticide use is subject to the Sustainable Use of Pesticides Directive (2009/128/EC), which regulates aerial spraying, establishes buffer zones, and prescribes operator training [13]. However, the lack of UAV-specific pesticide regulations creates interpretative gaps and delays in adoption across Member States [2].

Despite these limitations, some EU countries are moving faster in practice. Hungary has adopted detailed provisions under the FVM–GKM–KvVM regulations, explicitly allowing certain plant protection products to be applied by UAVs under strict technical conditions [14]. For instance, approved combinations such as Mospilan 20 SG (acetamiprid, 200 g/kg) + Combi-protec (protein-based attractant/adjuvant) for cherries and walnuts, Coragen 20 SC (chlorantraniliprole, 200 g/l) + DropMax (organosilicone-based adjuvant) for maize, and Amistar Sun 325 SC (azoxystrobin + difenoconazole) + Arrest (herbicide; active ingredient to be confirmed for the specific formulation) for sunflower are listed, each with mandatory operational requirements (spray volume, flight altitude, maximum wind speed, droplet size) [14]. This positions Hungary as one of the frontrunners in regulating UAV spraying at the national level.

A cross-regional comparison reveals that while the United States emphasizes safety and airspace control, the European Union focuses on risk categorization and harmonization, and Asia promotes rapid adoption through policy incentives. The diversity of approaches underscores the absence of a universal framework and the need for international coordination, particularly in the fields of equipment certification, environmental protection, and operator training.

Table 1. Comparative overview of UAV spraying regulation.

Region / Country	Status of UAV spraying regulation	Key strengths	Key limitations
Asia (Japan, China)	Japan – regulated since 1990s; China – massive adoption with subsidies	Large-scale adoption, established operator training (Japan), rapid expansion (China)	Standardization of equipment and drift control remain challenges
United States	FAA Part 107 + Part 137 (dual compliance with EPA pesticide laws)	Clear aviation framework; Remote Pilot Certificate; LAANC system for airspace access	Complex, outdated pesticide rules; UAV spraying requires exemptions
European Union (general)	EASA framework (open/specific/certified categories) + SUD Directive on aerial spraying	Harmonized aviation safety rules; risk-based categories	Lack of UAV-specific pesticide registration at EU level; implementation varies by state
Hungary	National FVM–GKM–KvVM regulations allow UAV spraying; list of approved pesticide combinations	One of the first EU countries with official pesticide authorizations for UAV use	Strict technical conditions; limited range of approved products
Switzerland	National rules since 2019; UAV spraying permitted in steep vineyards under authorization	Homologation system for UAV sprayers; >440 ha treated (mainly vineyards) by 2023	Permitted only in specific crops/ conditions; high regulatory burden
Germany	Special permits issued for UAV spraying in certain regions	Early pilot projects; safety assessments in progress	Limited, case-by-case approvals; not yet mainstream
Serbia	No UAV-specific pesticide registration; UAV spraying not explicitly regulated	Growing farmer interest; market availability of UAV sprayers	No UAV-specific laws; no pesticides registered for UAV application; no training pathway

3. National Framework: Serbia

In Serbia, the use of UAV systems for chemical crop protection is still in its early stages and is shaped by a fragmented regulatory environment. The current framework is primarily derived from the Law on Air Traffic and general provisions on pesticide application. However, there are no UAV-specific laws that directly regulate chemical spraying operations, which creates significant legal uncertainty for both manufacturers and end users [15].

Aviation regulations

According to the Civil Aviation Directorate of the Republic of Serbia, UAVs fall under general aviation rules [16]. Operators must register their UAVs and, depending on weight and purpose, obtain special permits for flights beyond visual line of sight or in controlled airspace. These rules are designed for flight safety rather than agricultural use, which mean that UAV spraying currently lacks clear national authorization procedures.

Plant protection regulations

UAV pesticide application is indirectly regulated through the Law on Plant Protection Products and associated bylaws. While aerial application of pesticides is formally permitted under certain conditions, the law does not explicitly reference UAV systems. As a result, UAV operators must navigate requirements originally designed for manned aerial spraying, such as protective buffer zones, operator qualifications, and product authorization. This creates practical obstacles, since UAV sprayers cannot be directly equated with conventional aircraft.

Market adoption and practice

Despite regulatory gaps, the Serbian market for UAV sprayers has expanded in recent years. Local distributors have introduced advanced models such as the DJI Agras T50 and EAVision J100, while demonstrations and pilot projects have been reported in both orchards and field crops. Articles in the professional press emphasize the increasing farmer interest and document field trials of products like the XAG P100 Pro for herbicide application. The reports suggest that the practical adoption of UAV spraying is outpacing the regulatory process, mirroring trends in other developing markets [15]. The primary regulatory barriers in Serbia include:

- Lack of UAV-specific legal provisions for pesticide spraying.
- Certification gap: UAV sprayers and atomizers are not covered by national testing protocols (unlike conventional sprayers, which follow EN ISO standards).
- Absence of registered pesticides for UAV application: currently, no plant protection products in Serbia are officially approved for UAV spraying, which prevents legal large-scale deployment even when UAV equipment is available.
- Operator training: there is no recognized training or licensing pathway for UAV plant protection operators.

- Institutional coordination: multiple authorities (aviation, plant protection, environment) have overlapping responsibilities but no unified framework.

Recent academic studies underline that without harmonized rules, UAV spraying in Serbia will remain limited to experimental or small-scale applications [15]. However, the growing market demand, coupled with international regulatory developments, is likely to accelerate the introduction of UAV-specific legislation in the coming years. Incorporating standards from the EU (SUD Directive) and aligning with ISO requirements for UAV sprayers are key steps toward enabling safe and sustainable adoption.

A particularly critical limitation is the absence of plant protection products registered for UAV application. Current legislation does not recognize UAV spraying as a distinct application method, meaning that no pesticide label in Serbia specifies UAVs as an approved technology. This effectively prohibits legal large-scale use, even though UAV equipment is available on the market. Recent field-based research in Serbia has shown that UAVs can provide effective herbicide application in wheat when flight parameters are optimized, but also emphasized that regulatory gaps in product registration remain a major obstacle [15, 17]. Bridging this gap, by introducing UAV-specific registration procedures for pesticides, is therefore essential for enabling wider adoption and ensuring safe, efficient, and environmentally responsible UAV-based crop protection.

4. Conclusion

The rapid advancement of UAV technology for chemical crop protection has opened up considerable opportunities for enhancing the efficiency, safety, and sustainability of pesticide use. Nonetheless, the regulatory landscape varies significantly across different regions. Asia has taken the lead in large-scale implementation, bolstered by specific policies, whereas the United States and the European Union have adopted more stringent regulations, focusing on airspace safety and environmental conservation.

In Serbia, the use of UAVs for spraying is still in its early stages, hindered by the absence of legislation tailored to UAVs, the lack of certification processes for UAV equipment, and the unavailability of registered pesticides suitable for aerial application. These shortcomings collectively obstruct the legal and widespread implementation of this technology, even as farmers show increasing interest and research indicates the agricultural benefits of UAV spraying.

To tackle these challenges effectively, a dual regulatory approach is essential. Initially, Serbia needs to synchronize its aviation and plant protection regulations with global best practices by implementing specific rules for UAV operator training, equipment certification, and safe operational procedures. Additionally, the Ministry of Agriculture, in partnership with pertinent agencies, should create a clear pathway for pesticide registration that acknowledges UAV spraying as an accepted application method. Aligning with EU standards, incorporating ISO guidelines for UAV sprayers, and encouraging pilot projects can lay the groundwork for wider acceptance and use.

By closing these regulatory gaps, Serbia and other Western Balkan countries can ensure that UAV-based spraying is not only technologically feasible but also legally secure, environmentally responsible, and aligned with the principles of sustainable agriculture.

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ANTIBIOTICS AND ANTIBIOTIC RESISTANT BACTERIA IN ENVIRONMENT: RISKS AND CONSEQUENCES TO PUBLIC HEALTH

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Abstract. Antibiotics are significant microbial compounds that are commonly utilized to treat bacterial illnesses. Their use began in the early twentieth century, and there have been numerous antibiotics created worldwide since then. Antibiotics saved millions of lives and increased plant productivity because of their benefits in human and animal medicine and plant agriculture. However, its broad use has had major environmental repercussions, including buildup in agricultural ecosystems and the food chain, as well as wastewater and sewage sludge. Antibiotics are overused in animal agriculture and the veterinary sector in comparison to human use, and this overuse is linked to antibiotics leaching into the environment via feces and urine, posing a high risk of antibiotic contamination in manure and the transmission of antibiotic-resistant genes.

The accumulation of antibiotics resulted in the creation of antibiotic-resistant bacteria, which entered the food chain. The majority of them are human pathogenic bacteria from a variety of genera, including Escherichia, Salmonella, Shigella, Listeria, and Campylobacter. These bacteria have antibiotic resistance genes and can cause serious health issues in humans. Antibiotics, such as tetracyclines, β-lactams, quinolones, macrolides, and sulfonamide, have been found in activated sludge, raw sewage, digested sludge, and treated effluents. Conventional wastewater treatment plants are not equipped to remove them. According to the literature, some bacteria found in agricultural ecosystems, food chains, and effluents may be multidrug resistant, which could have major ramifications for human health. This report summarizes the hazards and implications of antibiotic use and the occurrence of antibiotic-resistant microorganisms in the environment.

Keywords: antibiotic, antibiotic resistance bacteria, food chain, public health

1. Introduction

Antibiotics, microbial-derived chemicals that limit microbial development [1], are one of the most important inventions of the twentieth century [2], with widespread use in human medicine and agricultural productivity [3]. Selman Waksman and his associates coined the word "antibiotics" to describe substances capable of inhibiting microbial development [4]. These medicinal chemicals have saved human lives from infectious diseases throughout history [5]. Antibiotics were introduced in hospital procedures in the 1940s due to their great efficacy in pathogen eradication [6], and a wide range of antibiotics have been created and used since then, particularly during the 1940s and 1960s during the golden era of antibiotic use [7].

Because of the global increase in antibiotic use [8, 9] and antibiotic occurrence in diverse settings [10, 11], many countries have advocated proper antibiotic usage and reduction. In addition to the benefits, antibiotic use has been linked to an increase in antimicrobial resistance (AMR) and the emergence of antibiotic resistant bacteria (ARB) in a variety of environments [12], including aquatic ecosystems [13], soils [14], sewage sludge [15], the food chain [16], and so on.

In this paper, we summarized the origins, dangers, and threats that antibiotics and ARB pose to environmental quality and public health. Furthermore, this study emphasizes the relevance of methods in addressing AMR.

2. Origin of antibiotics and ARB in environment

Mouldy bread and therapeutic soil are the most ancient examples of antibiotic use from the middle of the second millennium BC [17]. During the Anglo-Saxon period (10th century), "Bald's Lechbook," a collection of medicinal writings, had recipes for combinations with probable antibacterial properties [18]. However, the credit for developing antimicrobial compounds goes to Paul Ehrlich, who synthesized salvarsan and neo-salvarsan around the turn of the twentieth century [19], and Alexander Fleming, who found penicillin in 1929 [20]. There have been numerous antibiotics created since ancient times [21], as showed in Figure 1.

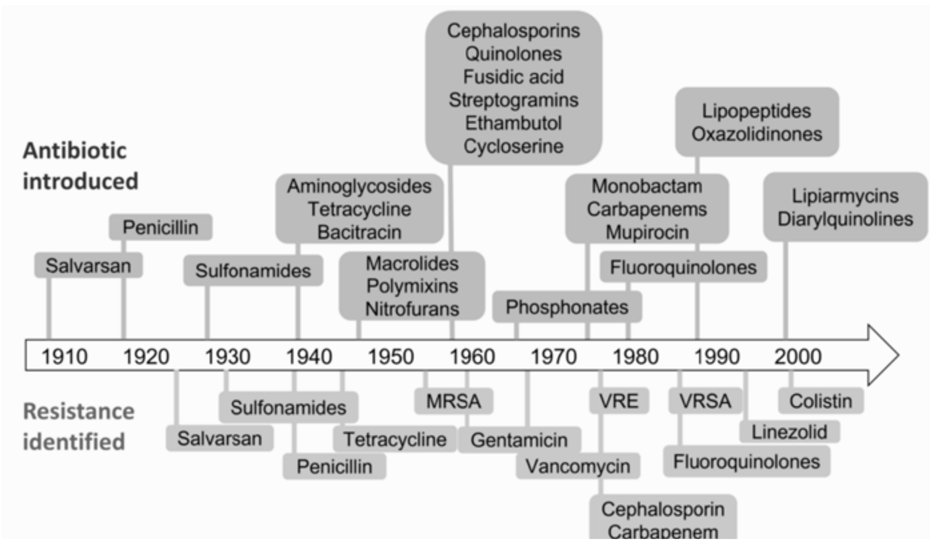

Figure 1. Development of antibiotics and antibiotic resistance in twentieth century (adopted from Salam et al. [22])

Antibiotics are produced as a result of metabolic activity in some bacteria, actinomycetes, and fungi; because of their benefits, antibiotics are widely utilized in human medicine and have saved millions of lives worldwide [23]. Antibiotics improve animal performance, enhance food safety, prevent illnesses, and save lives [24]. However, multiple studies have found that antibiotics are overused in animal agriculture and the veterinary sector when compared to human use [25]. Given that over billion tons of antibiotics have been synthesized since 1940 [26, 27], it is clear that this overuse is associated with antibiotics leaching into the environment via feces and urine [28], an increase in bacterial resistance to antibiotics, and the occurrence of risks to human health [29]. Bacterial resistance develops when bacteria are exposed to lower antibiotic concentrations than those with inhibitory or microbicide effects; these bacteria gain an advantage over other bacteria and become prevalent in a certain ecosystem [30]. ARB and resistance genes spread throughout the ecosystem by a series of phases [31]: gene movement within the genome, gene relocation, horizontal gene transfer, and physical transfer of bacteria to humans and/or animals. These bacteria can cause severe health problems in humans [32]. According to the CDC [33], antibiotic resistance causes more than 2.8 million infections and over 35,000 deaths in the United States each year. Some of ARBs and their resistance to various antibiotics are presented in the Table 1.

Table 1. ARBs and their resistance to antibiotics

ARB species	Resistance	Reference
Campylobacter spp.	fluoroquinolone	[34]
	macrolide	[35]
	erythromycin	[36]
Enterococcus spp.	amynoglycoside	[37]
	erythromycin, tetracycline	[38]
Escherichia coli	fluoroquinolone	[39]
	sulfonamide	[40]
	polymyxin	[41]
Listeria spp.	macrolide	[42]
	tetracycline	[43]
Salmonella spp.	β-lactams	[44]
	chloramphenicol, amynoglycoside	[45]
	colistin	[46]
Shigella spp.	β-lactams	[47]
	ampicilin, chloramphenicol	[48]

Due to overuse and improper practices in agriculture, and excretion by living organisms, antibiotics can be detected in all environments, as well as in wastewater treatment plants. Thus, antibiotics and ARB levels in agriculture, the food chain, and sewage sludge will be discussed further in the text.

3. Antibiotics and ARB in agricultural production: sources and consequences

Antibiotics are commonly used in plant and animal production [49], but their usage is restricted in several countries [50]. Antibiotics promote plant development and prevent infections [51]. Vidaver [52] stated that foliar spraying is the most common way for antibiotic use, while Batuman et al. [53] indicated that streptomycine and oxytetracycline are the most commonly used antibiotics in crop production. EPA allowed the use of these two antibiotics and kasugamycin in plant production [54], but with necessity of bacterial resistance monitoring. Fortunatelly, Williams-Nguyen et al. [55] revealed that use of antibiotics in crop cultivation is lower compared with human or animal treatment.

Antibiotics are used in animal agriculture to prevent disease and promote welfare [56]. Antibiotics are widely utilized in animal production [57]; however, 25 to 75% of the antibiotics used are not absorbed by the animal digestive tract and end up in the feces [58]. Depending on the species, several antibiotics might be employed in animal production (see Table 2).

Table 2. Antibiotics used in animal production

Type of animal	Antibiotics	Reference
swine	tetracyclines, macrolides	[59]
	benzylpenicillins	[60]
	amoxicillin	[61]
chicken	tetracycline, bacitracin, tylosin, salinomycin, virginiamycin, bambermycin	[62]
	colistin and fosfomycin	[63]
cattle	oxytetracycline, penicillin, streptomycin	[64]
	β-lactams, tetracyclines, aminoglycosides	[65]

Antibiotics accumulate in urine and/or feces [3], posing a high danger of antibiotic contamination in manure and the transmission of antibiotic-resistant genes [66]. The usage of this manure may alter the variety and organization of the microbial population in soil [67]. Popowska et al. [68] found that agricultural soils have a greater diversity of ARB species than forest soils. It is clear that the existence of antibiotic resistance genes in soil is determined by a variety of factors, including soil structure [69], the use of organic fertilizers [70], pH value, and salinity [71]. Heavy metals, on the other hand, infiltrate agricultural soils through agrochemical application (pesticides, mineral fertilizers), causing antibiotic resistance to develop and bacterial susceptibility to antibiotics to decrease [72]. These bacteria, once introduced into the food chain, produce serious diseases in humans [73].

3.1 Antibiotics and ARB in food chain

Antibiotic resistance has emerged as a global environmental issue as a result of its widespread usage in human treatment and agricultural productivity. Antibiotics may enter the food chain through a variety of routes after being released from crop fields, farms, and hospitals [74]. In any keys, Zhu et al. [75] and Wu et al. [76] identified agricultural soil, manure, and wastewater as "hot spots" of antibiotic presence in the environment. Antibiotic pollution of the environment, including residues and antibiotic resistance genes, can result in the presence of ARB in a variety of items such as fruits, vegetables, water, and feed, with major effects for human health [77].

Table 3 contains several examples of antibiotics found in feed, whereas Table 4 shows the incidence of ARB in the food chain.

Table 3. Occurence of antibiotics in feed

Type of feed	Detected antibiotic(s)	Reference
Capsicum annuum, Cucumis melo, Solanum melongena	sulfadiazine, sulfamethizole, tetracycline, doxycicline etc.	[78]
Lactuca sativa, Solanum lycopersicum, Brassica oleracea, Vicia faba	benzyl pyrimidines, fluoroquinolones, sulfonamides	[79]
milk	β-lactams, tetracycline, sulfonamides	[80]
beaf meat	oxytetracycline	[81]
hen eggs	enrofloxacin, sulfonamides, florfenicol	[82]
fish	clarithromycin, roxithromycin	[83]

Table 4. Occurence of ARB in feed and food chain

Type of feed	ARB detection and specifics	Reference
Cucumis sativus, Solanum lycopersicum, Citrullus lanatus	36 from 53 isolates were resistant to 5 of 8 antibiotics	[84]
fish and seafood	ARB isolates were resistant to gentamicin, chloramphenicol and tetracycline	[85]
spring onion	β-lactam-producing Shigella sonnei	[86]
irrigation and surface water	detection of multiresistant E. coli isolates	[12]

ready-to-eat vegetables	76.92 % of bacterial isolates were resistant to at least 5 antibiotics and 44.23% to over 10 antibiotics	[87]
potable water, meat, cheese, work surfaces	Gram negative bacteria: >50% of resistance to the 55% of the tested antibiotics; Gram positive bacteria: >50% of resistance towards 14% of antibiotics	[88]

4. Antibiotics and ARB in sewage sludge

Conventional wastewater treatment plants (WWTPs) are not specifically equipped to get rid of antibiotics; instead, these hydrophobic compounds are partially or fully adsorbed onto organic matter and solids within sludge, where they can accumulate over time [89]. Multiple classes of antibiotics including, tetracyclines, β-lactams, quinolones, macrolides and sulfonamide, have been frequently reported in activated sludge, raw sewage, digested sludge, and treated effluents [90]. Table 5 illustrates the prevalence of representative antibiotics from these classes in selected WWTPs of the globe. The persistence of antibiotics in sludge exerts selective pressure on microbial communities, facilitating the emergence and proliferation of resistant behavior among bacteria. Resistance is expressed through various mechanisms, including enzymatic degradation of antibiotics, modification of target binding sites, or reduced uptake of the pharmaceutical substance [90].

Table 5. Global occurrence of antibiotics in sewage treatment plant effluents (adapted from Samrot et al., [90])

Antibiotics	Concentration range (ng/L)	Wastewater treatment plant location
Cefalexin, Trimethoprim, Ciprofloxacin, Ofloxacin, Tetracycline, Sulfapyridine, Sulfamethoxazole, Azithromycin, Pipemidic Acid, Clindamycin	4.7-597.5	Portugal
Tetracycline, Trimethoprim, Sulfamethoxazole, Macrolides	40-550	USA
Ofloxacin, Norfloxacin, Cefalexin, Erythromycin, Sulfamethoxazole, Trimethoprim	5-7870	Hong Kong
Ciprofloxacin, Levofloxacin, Amoxicillin	60-1500	Iraq

Ampicillin, Ciprofloxacin, Gatifloxacin, Sparfloxacin, Cefuroxime	140-12,680	India
Metronidazole, Erythromycin, Ofloxacin, Trimethoprim, Azithromycin	0.11-0.22	South Africa
Tetracycline, Carbamazepine, Sulfadiazine, Trimethoprim, Clarithromycin, Roxithromycin	50-1069	Finland
Sulfapyridine, Azithromycin, Clarithromycin, Sulfamethoxazole	90-570	Switzerland
Clindamycin, Doxycycline, Azithromycin, Ciprofloxacin	41-422	Germany
Sulfamethoxazole, Clindamycin, Azithromycin, Ciprofloxacin	65-7494	Spain

The aforementioned traits are often acquired via spontaneous genetic mutations that generate antibiotic resistance genes, which can subsequently spread among microbial populations through horizontal gene transfer. For example, point mutations in ribosomal proteins have been shown to confer resistance to aminoglycosides, tetracyclines, and macrolides [91]. Furthermore, the agricultural application and disposal of sewage sludge in landfills introduces ARB and their related genes into terrestrial and aquatic ecosystems, increasing the risk of transmission to humans and other biota. Thus, WWTPs and their sludge systems represent critical hotspots for the evolution, enrichment, and propagation of ARB into the environment [92]. Notably, wastewater treatment process has been linked to the selective proliferation and development of multi-drug resistance (resistance to >3 antibiotics) in *Acinetobacter* spp. [93], underscoring the serious implications for public health.

5. Conclusion

The presence of drugs and antibiotic resistant microorganisms in the environment is a big global issue. This study summarizes the origins of antibiotics in diverse habitats, as well as the presence and prevalence of antibiotic-resistant bacteria in agricultural production, the food chain, and sewage sludge. Future initiatives will focus on ways for removing antibiotic-resistant microorganisms as well as the description of antibiotic alternatives in agriculture and health.

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INTEGRATED ANALYSIS OF THE SHEEP AND GOAT SECTOR IN ROMANIA IN THE PERIOD 2019–2024

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Abstract. The paper analyses the sheep and goat sector in Romania during 2019–2024, highlighting its strategic importance in the context of modern agriculture. The study highlights the high potential of sheep and goat farming, due to the favorable natural conditions, long tradition and high demand for products specific to these species. Spatial and statistical analysis reveals an uneven distribution of livestock and a general growth trend, especially in the case of goats. Milk production is stable, but the low level of profitability highlights a major dependence on subsidies. The study provides a detailed assessment of costs and the break-even point, showing that farms need to adopt efficient feeding and management strategies to remain sustainable. Comparatively, goat farming can be more profitable, but involves higher risks, while sheep farming is more financially stable. In conclusion, the sustainable development of the sector requires public support, digitalization, access to financing and continuous training of farmers.

Keywords: sheep and goat sector, sustainable development, economic profitability threshold, milk production

1. The importance of the sheep and goat sector

In all countries of the world, due to the accelerated growth of the human population, there is a call for rational use of resources, applying the most efficient technologies for raising and exploiting animals of zootechnical interest. The European integration of the Romanian agri-food sector takes place only under conditions of product competitiveness in a competitive environment.

The quantitative and qualitative increase in sheep and goat milk production must be based on clear information to ensure profitability. In the context of socio-economic instability and climate change, the sector is increasingly exposed to risks. Research must identify technically and economically efficient methods to achieve profitability and sustainable profit on the market.

Milk production and consumption have expanded globally, and trade in dairy products has experienced significant growth (Wiley, 2007). However, the multiple challenges currently facing the dairy sector affect the efficiency of farms and their level of profitability (Bórawski et al., 2020). Sustainable milk production is essential for ensuring human nutrition and health (Tricarico et al., 2020), but faces economic risks caused by price volatility, rising costs and the effects of climate change. Efficient use of production factors can significantly contribute to increasing the economic efficiency of dairy farms (Florence et al., 2018).

Low levels of economic efficiency in dairy production can have various causes, especially managerial ones, and can therefore have important economic consequences (Hogeveen et al., 2019). The current growing challenges and increased competition in the dairy industry highlight the need for farmers to analyze in depth the economic sustainability of farms (Fiorillo & Amico, 2024).

Those who decide to intensify their farm production systems can achieve higher levels of profit, but they must be able to sustain high investments and profit variability, which is influenced by the level of product value prices, or climate risks (Baudracco et al., 2022). The most important risks perceived by farmers are those of an economic and production nature, which requires the adoption of specific risk management strategies (Schaper & Theuvsen, 2014).

In this sense, the small ruminant sector in Romania presents considerable potential, due to the favorable pedoclimatic conditions, the long tradition in raising these species and the increasing demand for products derived from them, both on the domestic and foreign markets. In addition to the economic contribution, the sector also contributes significantly to maintaining the ecological balance, by valorizing pastures and lands with low agricultural potential, which cannot be exploited efficiently through other forms of agriculture. At the same time, these activities support employment in rural areas and the preservation of local traditions, playing an important role in the sustainable development of disadvantaged areas.

2. Spatial analysis of the dynamics of sheep and goat herds, as well as sheep and goat milk production

2.1. General information about the dynamics of sheep and goat farming in Romania

Sheep have experienced a steady increase in Romania due to the tradition of shepherds, geographical conditions and the quality of the products (milk and meat). The first official data show a herd of 4.4 million in 1860, which increased to 14 million in 1990. Subsequently, in 2001 the herd was halved, but between 2001 and 2024 it increased again by over 3 million heads, reaching about 74% of the maximum level in 1990. This evolution reflects the dynamics and importance of the sheep sector in Romania.

Goat herds in Romania have increased significantly, from about 364 thousand heads in 1938 to over 1,162 thousand heads after 1989. This increase was supported both by the reproduction of native populations and by imports of breeds specialized for milk production. However, most farmers use traditional growing and feeding technologies, and the development of this sector represents a challenge and a responsibility for optimizing the nutritional and technological process at the national level.

2.2. Analysis of statistical indicators calculated for sheep and goat herds

The analysis of statistical indicators related to sheep herds in Romania, distributed across the eight development regions, over the period 2019-2024, highlights a series of essential aspects related to their distribution and dynamics. Table 1 shows that the largest average sheep herds are recorded in the Center Region, followed by the North-West and North-East.

These concentrate an important part of Romania's herds (53.10%), indicating a long tradition and favorable conditions for sheep breeding. The South-East and West regions have moderate average herds. On the other hand, the South-Muntenia, South-West Oltenia and Bucharest-Ilfov regions have the lowest average herds, with values below 1 million heads, especially the Bucharest-Ilfov Region, where the average herd is only 17,527 heads, which reflects the predominantly urban and industrial specifics of this region.

The Center region presents the highest standard deviation (60.03), suggesting a high fluctuation of sheep numbers in these years. Also, significant deviations are observed in the Southwest Oltenia (40.22) and Northeast (30.13) regions, which indicate local instabilities caused by climatic, economic or farm management factors. In contrast, the Bucharest-Ilfov and Southeast regions record lower values of the standard deviation, which reflects a relative stability of the numbers, but the numbers are small.

The coefficient of variation provides an insight into the degree of relative dispersion in each region. The Bucharest-Ilfov region presents the highest coefficient of variation (0.46), indicating a very high instability of the numbers, which may be related to the urban character of this area. In contrast, the Southeast region has the lowest coefficient of variation (0.02), reflecting the high stability of the number of sheep. Regions with coefficients of variation between 0.016 and 0.062 show moderate stability, which is expected for areas with traditional agricultural activities.

Table 1. Indicators regarding sheep herds in Romania, by development regions in the period 2019-2024

	Min	Max	Average	Deviation	C.var.*	Annual rate
	thousands of heads					
North-West	1,765	1,839	1,813	29.32	0.01	0.40
Center	2,160	2,304	2,233	60.03	0.03	0.20
North-East	1,372	1,444	1,398	30.13	0.02	-0.25
South-East	1,565	1,620	1,598	20.44	0.02	0,17
South-Muntenia	930	1,004	978	30.11	0.03	-1.90
Bucharest-Ilfov	10	27	18	8.07	0.46	-21.88
South-West Oltenia	609	693	645	40.22	0.06	-3.02
West	1,538	1,620	1,572	38.18	0.02	1.09
Total	10,087	10,359	10,255	101.95	0.01	-0.14

Source: INSSE database, accessed 06.08.2025

The annual rate of variation shows the trend of sheep herds during the analyzed period. The North-West, Center, South-East and West regions register positive rates, which indicates a slight increase in herds in these areas. In particular, the West region has a positive annual rate of +1.09%, being the only one with a more consistent increase in this interval. In contrast, the North-East, South-Muntenia, Bucharest-Ilfov and South-West Oltenia regions show negative rates, a sign that sheep herds are decreasing in these areas.

It is worth noting the sharp decline in the Bucharest-Ilfov Region (-21.88%), which reflects strong urbanization and a decrease in traditional agricultural activities. The decrease in South-Muntenia (-1.90%) and South-West Oltenia (-3.02%) can be correlated with structural problems in agriculture, lack of investments or climate change affecting pastures and animal reproduction. Looking at the total per country, the average sheep population in the analyzed period is about 10.25 million heads, with a standard deviation of approximately 101,948, which indicates a relatively small variation compared to the total average, and the annual rate of - 0.14% suggests a general slightly downward trend at the national level.

In conclusion, the analysis by regions shows an uneven distribution of sheep herds in Romania, with traditionally strong areas in the Center and North-West, while other regions, especially those with urban characteristics or agricultural problems, are experiencing declines. These data can be useful for planning interventions and policies to support the sheep sector, by allocating resources, stimulating investments and developing infrastructure in regions with high potential, but also by finding adapted solutions for areas with declining herds.

Table 2. Indicators regarding goat herds in Romania, by development regions in the period 2019-2024

	Min	Max	Average	Deviation	C.var.*	Annual rate
	thousands of heads					
North-West	91	95	92	1.58	0.02	-0.42
Center	107	122	111	6.27	0.06	2.96
North-East	171	194	186	9.88	0.05	-3.03
South-East	268	334	306	26.97	0,09	-5.39
South-Muntenia	206	239	227	12.93	0.06	-3.68
Bucharest-Ilfov	4	13	8	4.19	0.55	-18.83
South-West Oltenia	236	253	243	7.43	0.03	-1.32
West	60	66	63	2.39	0.04	-1.01
Total	1,162	1,294	1,236	56.18	0.05	-2.66

Source: INSSE database, accessed 06.08.2025

During the period 2019-2024, the distribution of goat herds in Romania showed significant variations between development regions, highlighting both the zootechnical potential specific to each area and the trends in the evolution of the goat sector at national level. Goat herds in Romania recorded a constant increase, with a national average of approximately 1,236 thousand heads and an annual rate of +2.65%.

The South-East region stands out with the largest herds, with an average of 306 thousand heads and a rapid annual growth of +5.39%, reflecting a dynamic goat sector with high potential. South-Muntenia recorded a stable evolution, with an average of 227 thousand heads and a growth rate of +3.68%, supported by favorable conditions and diversified agriculture. The North-East of the country reported an average of 186 thousand heads and an increase of +3.03%, due to pastoral traditions and a large rural population (Table no. 2).

In South-West Oltenia, the average livestock was 243 thousand heads, with a more modest increase of +1.32%, indicating a constant but slow development. The Center Region recorded an average of 111 thousand heads, with a pace of +2.96%, supported by the growing demand for goat milk products. In contrast, in the North-West a slight decrease in livestock was observed (-0.42%), with an average of 92 thousand heads, which shows a weaker orientation towards goat breeding. The West Region has small livestock, around 63 thousand heads, but with a modest increase (+1.01%). The Bucharest-Ilfov region has a very low herd (7,550 heads) and a high fluctuation, although the annual rate is high (+18.83%), this aspect being influenced by the small numerical base and the urban character of the area.

In conclusion, the analysis by regions of the evolution of goat herds in the period 2019–2024 shows that the sector is in sustained growth in most areas, with an emphasis on the Southeast, Southeast Muntenia and Northeast. Goat farming is becoming an increasingly viable alternative for small farmers, due to lower costs, growing demand and the adaptability of goats to various environmental conditions.

Table 3. Indicators regarding sheep and goat milk production in Romania, by development regions in the period 2019-2023

	Min	Max	Average	Deviation	C.var.*	Annual rate
	thousands of heads					
North-West	863	1,031	915	66.59	0.07	0.60
Center	1,075	1,335	1,159	109.76	0.09	2.79
North-East	884	1,046	959	74.07	0.08	1.32
South-East	1,146	1,181	1,162	14.67	0.01	0.67
South-Muntenia	764	833	792	36.09	0.05	-2.05
Bucharest-Ilfov	18	40	29	9.88	0.34	-17.04
South-West Oltenia	653	737	700	31.87	0.05	-0.95
West	598	694	639	37.76	0.06	1.85
Total	6,060	6,585	6,355	200.12	0.03	0.69

Source: INSSE database, accessed 06.08.2025

The third indicator analyzed concerns the production of sheep and goat milk, which is treated as a unit, as there are no separate official reports for each species. The statistical data provided by the National Institute of Statistics present this production in a cumulative form, which requires an aggregate approach at the level of interpretation. Consequently, the analyzed indicators together reflect the production resulting from the exploitation of both species, without the possibility of quantitative dissociation between sheep and goat milk. Sheep and goat milk production is an essential indicator for evaluating the performance of the sheep and goat sector in Romania, reflecting not only the size of the herds, but also the operating efficiency, the technological level and the capacity to capitalize on livestock production. During the period 2019–2024, an average annual production of 6,355 thousand hectoliters was recorded at the national level, with a minimum of 6,060 thousand hl and a maximum of 6,585 thousand hl. This narrow range and the relatively small coefficient of variation (0.03) indicate good stability of total production (Table 3).

The Center region has consistently been among the leaders in sheep and goat milk production, with an annual average of 1,159 thousand hl and a growth rate of +2.79%. The coefficient of variation, of 0.09, shows a slight fluctuation, but the overall evolution is positive. This performance can be explained by the existence of large herds, favorable pedoclimatic conditions and a consolidated milk processing network. The Southeast region stands out with an average production of 1,162 thousand hl, but with a much lower variability (C.var 0.01) and an annual rate of +0.67%. These data suggest a remarkable stability of the sector in this region, probably due to the efficient organization of farms and adaptability to market requirements. North-East Romania recorded an average of 959 thousand hl, with a positive evolution of +1.32% annually. The coefficient of variation (0.07) indicates a slight fluctuation, reflecting moderate changes in production conditions. The North-West of the country had an average production of 915 thousand hl and a moderate annual rate of +0.60%. The coefficient of variation (0.07) suggests a decent stability, but with a slight tendency to expand.

The region benefits from varied relief and solid traditions in animal husbandry, but investments are more modest compared to the Center or the Southeast. The West region presents an average of 639 thousand hl and a positive rate of +1.85%, with a coefficient of variation of 0.06, a sign that the sector is in a slow but sustained growth. Despite a relatively small number of goats in this region, the yield per head of animal or the modernization of farms could explain this favorable evolution. South-West Oltenia records an annual average of 700 thousand hl, with a slight decrease. The coefficient of variation (0.05) shows a relatively constant production, but the downward trend signals the need for interventions to stimulate farm efficiency and higher production value.

The South-Muntenia region produced, on average, 792 thousand hl, with a negative rate of -2.05%, which indicates a constant decrease during the analyzed period. Although the coefficient of variation (0.05) is moderate, the downward trend could be associated with the reduction of herds, the decrease in profitability in some areas or the reorientation of farmers to other activities.

The Bucharest-Ilfov region is, again, a special case: with a very low average production (29 thousand hl) and an extremely high fluctuation (C.var 0.34), the region faces instability and lack of specialization in the field. The negative annual rate of -17.04% suggests a strong contraction of the activity, which is to be expected in an urbanized area, where animal husbandry has a marginal role. Statistical data on sheep and goat milk production in the period 2019–2023 highlight a general trend of stability and slight growth at the national level, with some regional exceptions.

The Center, Southeast and Northeast regions assert themselves as the main production poles, both through the volumes generated and through the positive annual developments. On the other hand, South-Muntenia, Southwest Oltenia and Bucharest-Ilfov show significant decreases, which may reflect either structural changes in the holdings or economic and market difficulties.

3. CALCULATING THE BREAK-EVEN POINT

The cost of animal products is mainly determined by feed costs, which can reach weights of over 50-65%. Expenses are influenced by internal and external factors, such as market conditions and input prices, but feed remains the main cost component. Therefore, the increase in input prices, especially feed and energy, seriously affects profitability.

The lack of subsidies comparable to those in other European countries disadvantages Romanian farmers, limiting investments and technology. Reducing costs through efficiency, innovation and consumption optimization is the only viable solution for competitiveness.

At the national level, the main criterion is overall productivity, and at the farm level it is profitability. Profitability indicators are the most representative for evaluating economic performance, contributing to determining profit and the rate of return.

For the calculation of profitability in the case of sheep's milk, the technological estimate and the product budget were taken into account, for an average production of 60 liters/sheep. The structure of expenses reflects the average costs for maintaining an animal, expressed in lei/head. Expenses are divided into two large categories: variable expenses and fixed expenses, totaling lei 841.9/head.

The largest share is held by variable expenses, which amount to lei 673.5/head, representing approximately 80% of the total costs. Within these, the expenses for feed are the highest, respectively lei 543.7/head, i.e. over 64% of the total. This highlights the fact that animal feeding is the main cost element in a livestock farm.

Other significant variable expenses include biological material (lei 70/head), medicines and sanitary materials (lei 19.11/head), energy and fuel (lei 16.42/head), as well as smaller expenses related to supplies, insurance and other materials. Fixed expenses amount to 168.3 lei/head and include costs that do not vary directly with the number of animals, such as: labor (133.2 lei/head), interest on loans (23.6 lei/head), general administrative expenses (9.9 lei/head) and depreciation of fixed assets (1.6 lei/head).

This expenditure structure indicates an economic activity in which production costs are dominated by material and consumable resources, especially feed. Fixed costs are relatively low, which offers a certain flexibility depending on the volume of production. In order to obtain a profit or to optimize the economic efficiency of the activity, rigorous control of feed expenses and efficient management of financial resources are essential.

The analysis of economic indicators related to the zootechnical activity highlights a balanced but fragile financial situation, in which profitability is essentially supported by the subsidies granted. The total value of the production obtained is 843 lei/head, the equivalent of 14.05 lei per liter of milk, but only 336 lei/head (5.60 lei/liter) comes from the main production, i.e. from the sale of milk. The difference is covered by secondary income and subsidies, the latter totaling 24.6 lei/head or 0.41 lei/liter.

Thus, the gross product, which cumulates the value of production and subsidies, reaches 867.6 lei/head, respectively 14.46 lei/liter. On the other hand, the total expenses associated with the activity are 841.9 lei/head, i.e. 14.03 lei/liter, which indicates a fragile balance between income and costs. The largest part of these expenses is represented by the variable ones, amounting to 673.5 lei/head (11.23 lei/liter), within which the costs of feed occupy a central place – 543.7 lei/head or 9.06 lei/liter.

Fixed expenses, amounting to 168.3 lei/head (2.81 lei/liter), are dominated by labor costs and interest on loans. The economic result is modest: taxable income is only 1.1 lei/capita, respectively 0.02 lei/liter, which means that the profit obtained from the activity, before the application of subsidies, is insignificant. Net income, including subsidies, amounts to 25.6 lei/capita or 0.43 lei/liter. Under these conditions, the taxable income rate is only 0.3%, and the net income rate with subsidies reaches 7.7%, indicating a low overall profitability.

The production cost of a liter of milk is estimated at 5.58 lei, and the selling price on the domestic market is 5.60 lei/liter. Thus, the gross profit from the sale of a liter of milk is only 0.02 lei, which demonstrates an extremely low margin. Without subsidies, the activity would be practically unprofitable.

Table 4. Budget for sheep milk product - average production 60 l/head

INDICATORS	Lei/head	Lei/literof milk
A. PRODUCTION VALUE	843,0	14,05
A1. Of which main production	336,0	5,60
B. SUBSIDIES	24,6	0,41
C. GROSS PRODUCT	867,6	14,46
D. TOTAL EXPENSES	841,9	14,03
D1. Of which for main production*	334,9	5,58
I. VARIABLE EXPENSES	673,5	11,23
1. Feed expenses	543,7	9,06
2. Biological material	70,0	1,17
3. Electricity + fuel	16,4	0,27

4. Medicines and sanitary material	19,1	0,32
5. Other material expenses	14,0	0,23
6. Supply quota	9,5	0,16
7. Insurance	0,8	0,01
II. FIXED EXPENSES	168,3	2,81
8. Labor expenses	133,2	2,22
9. General expenses	9,9	0,17
10. Interest on loans	23,6	0,39
11. Depreciation	1,6	0,03
E. TAXABLE INCOME	1,1	0,02
Taxes and fees	0,1	0,00
F. NET INCOME + subsidy	25,6	0,43
G. TAXABLE INCOME RATE (%)	0,3	0,3
H. NET INCOME RATE + subsidies (%)	7,7	7,7
COST OF PRODUCTION	334,9	5,58
DOMESTIC MARKET PRICE	336,0	5,60

Source: R. Chetroiu & all, 2020

The break-even point represents the minimum sales volume required for the farm to cover all costs and avoid losses. It can be calculated in value units (lei) or in physical units (liters) using the formulas:

Breakeven point in value units (lei) (Vâlceanu G. & all, 2004):

$$PR_{lei} = \frac{\text{Fixed expenses}}{1 \quad \frac{\text{Variable expenses}}{\text{Total income}}} = 841{,}9 \text{ lei} \qquad (1)$$

In terms of value, the minimum income required to cover total expenses is 841.9 lei per head of animal. Only above this level does an effective profit appear.

Breakeven point in physical units (Vâlceanu G. & all, 2004):

$$PR_{fiz} = PR_{lei} / \text{ Price per liter} = 150{,}34 \text{ liters/animal} \qquad (2)$$

This is approximately 150.34 liters/head, which means that any production below this level, at the current selling price, leads to financial losses. Reducing feed costs by 10% leads to a decrease in total costs per head from 841.9 lei to 787.53 lei, i.e. a saving of 54.37 lei/head. As a result, the physical break-even point decreases from 150.34 liters to 140.63 liters/head, which means that the farm can become profitable at a lower milk production.

This adjustment has a significant impact on the farm's economic safety margin, providing a small buffer against potential risks. A 10% increase in feed costs has a negative effect on the economic balance, leading to an increase in total costs by 54.37 lei/head, respectively an increase in the physical break-even point by approximately 10 liters/head compared to the baseline situation. In practice, this means that the farm will have to produce more milk per animal, just to cover the new costs.

In conclusion, the activity under analysis operates close to the economic profitability limit, with a precarious balance between income and expenses. Profitability is ensured almost exclusively through subsidies, and volatility of market prices or a decrease in production can quickly turn this activity into an unprofitable one. Therefore, rigorous management of costs, especially those for feed, and an improvement in productive efficiency are necessary to ensure the economic sustainability of the farm.

The analysis of expenses related to goat raising reveals a complex cost structure, in which variable expenses predominate, but fixed expenses also have a significant share. The total value of expenses per head of animal is 1,612.9 lei, an amount that includes both direct costs related to the maintenance and production of goats, as well as indirect and administrative expenses. Of the total expenses, variable expenses amount to 894.1 lei/head, which represents approximately 55.4% of the total. Within these, the highest costs are associated with feed, which reach 757 lei/head, representing over 84% of the total variable expenses.

This aspect highlights the high dependence of the farm on the price and quality of feed, but also the importance of a balanced and economical ration. Other variable expenses include biological material (67.5 lei), energy and fuel (19.55 lei), medicines and sanitary materials (21.28 lei), as well as other material expenses, supply quota and insurance, all with modest values, but necessary for the daily operation of the farm.

Fixed expenses amount to 718.8 lei/head, i.e. 44.6% of the total costs. The largest share in this category is occupied by labor costs, amounting to 666 lei/head, which represents approximately 92.7% of fixed expenses and 41% of the total expenses per head. This highlights the fact that the zootechnical activity is labor-intensive, requiring constant involvement of personnel. General expenses, interest on loans and depreciation of equipment have a low share, but still reflect the existence of previous investments and administrative operating costs.

In conclusion, the structure of technological expenses for goat farming highlights an economic profile in which food and labor represent the main sources of cost. Optimizing these two components, through efficient feed rations and the technology of the activity, can have a significant impact on the overall profitability of the farm. Careful management of these expenses is essential to ensure the economic viability of the goat farm, especially in a competitive and volatile context in terms of input prices.

The economic analysis of the goat farm highlights a profitable activity, but dependent on strict cost control and the level of the capitalization price. The total value of production per head of animal is 1,703 lei, which corresponds to an average of 6.31 lei/liter of milk, of which the main production, represented by goat milk, brings 1,269 lei/head, i.e. 4.70 lei/liter. This price level reflects an average capitalization of production in the context of the domestic market.

Feed costs represent an essential component in the cost structure of goat raising, having a direct impact on production profitability. In the analyzed case, the annual ration per goat amounts to 2,540 kg of feed, with a total value of 757 lei, which determines an average cost of approximately 0.30 lei/kg. From a quantitative point of view, green mass occupies the largest share in the diet, with 1,600 kg/head, i.e. almost 63% of the total feed, followed by succulents (450 kg) and hay (270 kg). In contrast, concentrated and coarse feed are administered in smaller quantities: 150 kg and 70 kg per goat annually, respectively. However, if we analyze the value structure of expenses, we observe that the ratio between quantity and cost is not always proportional.

Table 5. Goat milk product budget - average production 270 l/head

INDICATORS	Lei/head	Lei/liter of milk
A. PRODUCTION VALUE	1,703.0	6.31
A1. Of which main production	1,269.0	4.70
B. SUBSIDIES	24.6	0.09
C. GROSS PRODUCT	1,727.6	6.40
D. TOTAL EXPENSES	1,612.9	5.97
D1. Of which for main production*	1,178.9	4.37
I. VARIABLE EXPENSES	3.31	894.1
1. Feed expenses	757.0	2.80
2. Biological material	67.5	0.25
3. Electricity + fuel	19.5	0.07
4. Medicines and sanitary material	21.3	0.08
5. Other material expenses	15.2	0.06
6. Supply quota	12.7	0.05
7. Insurance	0.8	0.003
II. FIXED EXPENSES	718.8	2.66
8. Labor expenses	666.0	2.47
9. General expenses	13.2	0.05
10. Interest on loans	31.3	0.12
11. Depreciation	8.3	0.03
E. TAXABLE INCOME	90.1	0.33

Taxes and fees	9.0	0.03
F. NET INCOME + subsidy	105.7	0.39
G. TAXABLE INCOME RATE (%)	7.6	7.65
H. NET INCOME RATE + subsidies (%)	9.0	8.97
COST OF PRODUCTION	1,178.9	4.37
DOMESTIC MARKET PRICE	1,269.0	4.70
INDICATORS	Lei/head	Lei/liter of milk

Source: R. Chetroiu & all, 2020

Feed costs represent an essential component in the cost structure of goat raising, having a direct impact on production profitability. In the case analyzed, the annual ration per goat amounts to 2,540 kg of feed, with a total value of 757 lei, which determines an average cost of approximately 0.30 lei/kg. From a quantitative point of view, green mass occupies the largest share in the diet, with 1,600 kg/head, i.e. almost 63% of the total feed, followed by succulents (450 kg) and hay (270 kg). In contrast, concentrated and coarse feed are administered in smaller quantities: 150 kg and 70 kg per goat annually, respectively. However, if we analyze the value structure of expenses, we observe that the ratio between quantity and cost is not always proportional.

Total production-related expenses amount to 1,612.9 lei/head, or 5.97 lei/liter, of which the main production expenses are 1,178.9 lei/head, or 4.37 lei/liter – practically representing the production cost of one liter of milk. In the structure, variable expenses are dominant, amounting to 894.1 lei/head (3.31 lei/liter), with a share of approximately 55% of the total. Of these, feed expenses are the most important, representing 757 lei/head or 2.80 lei/liter, or over 84% of the total variable.

The other variable expenses, such as biological material, energy, medicines, sanitary materials and other miscellaneous expenses, are relatively small in weight, but necessary for the balanced functioning of the production system. For example, the expenses for medicines and sanitary materials are 21.3 lei/head (0.08 lei/liter), reflecting the concern for animal health, and energy and fuel – only 0.07 lei/liter – show a relatively low energy consumption, specific to goat farming.

Fixed expenses are also significant, totaling 718.8 lei/head (2.66 lei/liter), of which labor represents the majority component, with 666 lei/head or 2.47 lei/liter – that is, over 92% of fixed expenses. This figure confirms the labor-intensive nature of this type of farm, where many activities require manual or semi-mechanized intervention.

The economic result is positive: taxable income is 90.1 lei/head, respectively 0.33 lei/liter, which leads to a taxable income rate of 7.6%. If subsidies are also taken into account, the net income reaches 105.7 lei/head, respectively 0.39 lei/liter, and the net income + subsidies rate increases to 9%, a reasonable level for an agricultural activity. Comparing the production cost (4.37 lei/liter) with the market price (4.70 lei/liter), the result is a gross profit of 0.33 lei/liter, i.e. an acceptable economic margin, but relatively sensitive to price fluctuations or production variations..

This underlines the importance of rigorous management of costs, especially feed and labour, and highlights the vulnerability of the sector in the absence of subsidies or in the event of a decrease in the selling price. For a goat to cover all production costs (both variable and fixed), it must produce at least 343 litres of milk/year, at the current average price of 4.70 lei/litre. Below this threshold, the activity becomes unprofitable.

A 10% reduction in feed costs lowers the physical break-even point from around 343 litres to 327 litres/milk per goat/year, facilitating a faster profit and reducing pressure on production. Conversely, a 10% increase in feed costs raises the break-even point to 359 litres, meaning that higher production or a better price for milk is required to avoid losses.

For a farm with 1,000 heads, the break-even point is calculated for both sheep and goat farming to assess which activity is more profitable. For goats, the physical break-even point is 343,000 liters, and the value threshold is 1,612,900 lei. For sheep, the physical break-even point is 169,000 liters, and the value threshold is 842,000 lei. In comparison, goats require double the milk production to cover costs, but the total costs per head are almost double that of sheep.

Goats have a profit rate of approx. 9% with subsidies, and sheep approx. 7.7%. Although the breakeven point is higher for goats, they offer slightly higher profitability potential, due to better production and prices. Sheep have lower costs and a lower breakeven point, being more accessible and less risky.

In conclusion, for a farm of 1000 heads, goats can bring higher profits in the medium and long term. However, sheep farming is safer for farms with limited resources or unstable markets.

5. Conclusions

In order to ensure a balanced and sustainable development of the sheep and goat sector in Romania, it is necessary to adopt an integrated strategy that responds to both regional specificities and current economic, climatic and social challenges. Given the strategic importance of this sector for the rural economy, employment and food security, the proposed measures must aim to increase the competitiveness of farms and adapt to the requirements of the European market.

An essential step is to encourage investments in areas with high potential, good infrastructure and tradition in sheep and goat farming. Modernising farms and introducing advanced technologies can create successful models that can be replicated in other regions. In declining areas, tailored support is needed, through access to credit, subsidies and vocational training, to stabilise production and preserve traditional activities.

The modernisation of milk collection and processing infrastructure is also crucial, as the lack of adequate equipment limits farmers' access to competitive markets. Therefore, a coherent strategy for the development of this sector must be based on smart regional investments, differentiated support policies and modern infrastructure. Only through such an approach can a real balance be achieved between economic development, environmental protection and social cohesion in rural areas. Strengthening this sector will allow Romania to become a more competitive player on the European agri-food market and, at the same time, ensure the long-term sustainability of farms and agricultural communities.

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ANALYSIS OF SOYBEAN PRODUCTION AND POTENTIAL SECONDARY APPLICATION

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Abstract. In addition to the grains as the main agricultural product, the agricultural production of soybean also produces large quantities of plant residues in the form of soybean straw. The article focuses on the primary trends in soybean production worldwide, and Serbian's current position in global production. The paper analysis the dynamics and structure of sown areas, gross harvest volumes and soybean yields in the world for the period 2006-2023 in the context of leading producing countries. Soybean straw is an agricultural leftover that yields up to 1.5 kg per kg of soybeans. The existing literature demonstrates the vast potential of soybean straw as an environmentally friendly source of carbon to produce chemicals, materials, fuels and energy similar to oil refineries.

The possibility of using untreated soybean straw for the synthesis of building materials was considered. Different types of common cement were used as starting raw materials for synthesis. The characterization of two test samples was performed using X-ray diffraction analysis (XRD), light microscopy (LM), thermal conductivity and heat capacity measurement.

Keywords: soybean production, soybean straw, eco-friendly material, agricultural residues, building material

1. Introduction

According to data on soybean production in Europe and the world in the period from 2006 to 2023, the countries of the Americas, namely Brazil, the USA and Argentina, are leaders in the global production of this agricultural crop (Figure 1 [1]), whose total production in the last year of the period observed is almost 80% of total world production, i.e. 371.17 million tonnes. In Europe (Figure 2 [1]), the trend in relative production growth is much stronger in the period under review, but production is much lower, amounting to 14.88 million tonnes. Europe's leading countries in soybean production: Russia, Ukraine and Italy produce just over 80% of the total production of this grain in Europe, while Serbia is in fourth place with around 0.6 million tonnes. The growth in soybean production is a consequence of increasing consumption, which is linked to the use of soybean as animal feed in livestock farming on the one hand, and as a source of vegetable protein in human nutrition on the other [2].

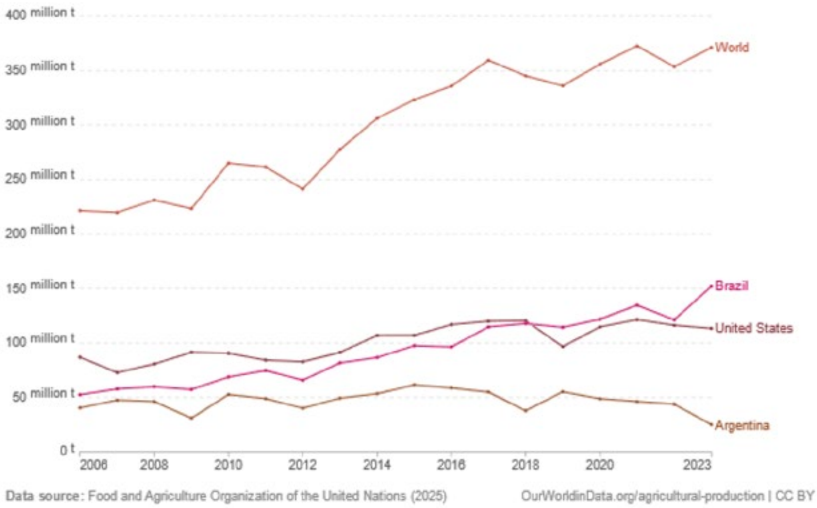

Figure 1. Soybean production in the World [1].

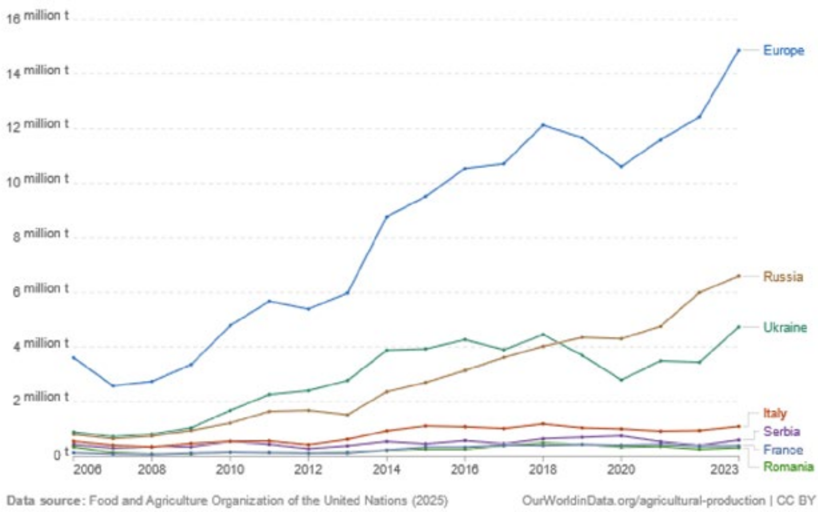

Figure 2. Soybean production in the Europe [1].

In, addition to the grains, as the main agricultural product, the agricultural production of soybean also produces large quantities of plant residues, namely soybean straw, which exceeds the actual grain in mass and amounts to 1.5 kg per kg of grain [3]. Straw, as a crop residue, used to be collected together with the main product and used in animal husbandry and in the household. The introduction of modern livestock farming methods has minimised the need for straw in livestock farming. This is because crop residues are more often left on the production site, where they make soil cultivation more difficult, so many farmers, burn the straw in the fields to remove unwanted material. This solution is not suitable for several reasons. The risk of fire is increased by the dry vegetation and the wind, which can quickly exacerbate the flames, causing considerable damage to property and often endangering human lives. In addition, burning straw releases carbon dioxide, particulate matter and other harmful gasses into the atmosphere, which contributes to global warming due to a higher concentration of triatomic gases in the atmosphere [4].

The existing literature shows the vast potential of soybean straw as an environmentally friendly carbon source to produce value-added chemicals, materials, fuels, and energy in a similar way to oil refineries [3].

With the aim of finding a use for this type of biomaterial that is in line with the country's green energy transition and thus avoid burning it in the fields, this paper investigated the possibility of using untreated soybean straw for the synthesis of building material.

Two building material samples were randomly prepared from different types of cement and untreated soybean straw, and their composition was not precisely determined. Therefore, the partial characterisation of these two test samples was carried out using X-ray diffraction analysis (XRD) and light microscopy (LM). In addition, the proportion of combustible materials in the samples was determined by the ashing process, and the values of thermal conductivity and specific heat capacity were also measured, as two fundamental thermal properties that are important for building envelopes.

2. Materials and Results

The global growth of the construction industry leads directly to increased consumption of natural resources, energy and waste production. One of the most important materials in this industry is concrete, whose global production amounts to 4.4 billion tonnes per year and is expected to increase to 5.5 billion tonnes by 2050 [5].

In the composition of concrete, aggregate accounts for more than 70% of the volume, and the properties of concrete mixtures and hardened concrete depend on its properties. It provides compressive strength and gives the concrete mix durability, strength, workability and suitability for the execution of work. It can be present in natural and artificial, smaller and larger grain sizes.

The extraction and processing of natural mineral aggregates consumes a large amount of energy, and the use of natural sand, gravel and other non-renewable materials has a negative impact on the environment. On the other hand, some researchers have concluded in recent years that the addition of fibres in certain quantities can improve the performance of concrete [6,7]. However, most man-made fibres are expensive, so research has focused on natural, plant-based, low-cost (or waste) fibres that could improve the properties of concrete [5,8,9,10].

Biomass of different origins can be used in an inorganic basis [5,8,9,10,11], e.g. lime and cement, for the production of bio-based building materials in the construction industry. Which of these materials can be used depends on its intended use in construction, the required properties of the material, the climate in which it is used and its availability. As with the use of biomass for energy production, the principle that regional biomass raw materials are more sustainable than those from distant regions should also apply to the production of bio-concrete in the construction industry. More specifically, it is preferable to use the biomass that is most readily available and close to the place where the bio-concrete material is produced.

Biomass can be used to produce building materials for various applications, e.g. as a component of load-bearing building materials, as filling material, insulating material and plaster material. These materials differ in their structure depending on the area of application. Plant fibres can be combined with binders and then used in construction to fulfil thermal or structural functions. The behaviour of concrete based on plant fibres is mainly determined by the fibre content in the concrete matrix. Several studies have shown that increasing the proportion of these lignocellulosic fibres increases porosity and moisture buffering capacity on the one hand, but reduces density, thermal conductivity and compressive strength on the other [12].

As mentioned in the introduction, soybean straw is a by-product of soybean cultivation in Serbia, and considering the growing soybean production in recent decades, this type of straw certainly represents a raw material that is available in large quantities and for which it would be desirable to find a use. Straw consists mainly of cellulose, hemicellulose and lignin, which are also components of wood, but differ significantly in quantity, chemical composition and morphology [13].

2.1 Test Materials

Two experimental, randomly shaped samples of building materials, were taken from a small building materials factory in Vojvodina (granary of Serbia) to test their possible use in the construction of buildings. The samples were made on the basis of lime cement with the addition of untreated soybean straw (Figures 3 and 4).

Figure 3. Sample 1

Figure 4. Sample 2.

The sample densities listed in Table 1 were calculated by measuring the volume and weight of the two samples.

2.2 Thermal characteristics

The thermal conductivity and specific heat capacity of these materials, two fundamental physical quantities whose values influence thermal comfort in buildings, were measured using the Thermtest Measurement Platform (MP-2) device. Three holes were drilled in both samples to place the probe of the measuring device and the measurement was carried out once or twice in each sample hole. Table 1 shows the mean values of these measurements. The thermal conductivity measurements were performed with a small standard deviation for both samples. Although the specific heat capacity values are the same, the measured values for the sample 2, were more different from each other, i.e. the standard deviation of these measurements was significantly higher, indicating a greater inhomogeneity of this sample.

If one compares the values determined with the usual building material solid brick (density 1600-1800 kg/m^3, specific heat capacity 0.92 kJ/kgK, thermal conductivity 0.64-0.76 W/mK) or hollow brick (density 1200-1400 kg/m^3, specific heat capacity 0.92 kJ/kgK, thermal conductivity 0.52-0.61 W/mK) [14], it can be said that these materials have lower values for density and thermal conductivity, which is positive for building materials. The measured values of specific heat capacity are lower, which is negative from the point of view of thermal comfort in buildings.

To determine the proportion of straw in the two samples analysed, both materials were ashing at temperatures of 550 °C, 815 °C and 950 °C; the results are shown in Table 2. The results show that the mean values of the combustible fraction are higher for sample 2, which is due to a slightly higher straw content.

Table 1. The test material's physical properties.

Sample	Density (kg/m3)	Thermal conductivity (W/mK)	Thermal capacity (kJ/kgK)
Sample 1	832	0.18	0.37
Sample 2	745	0.22	0.37

Table 2. The percentage of combustibles ascertained upon ashing

Ashing temperature (°C)		Mass fraction of sample 1 material (%)			Mass fraction of sample 2 material (%)		
		(1)	(2)	(3)	(1)	(2)	(3)
550	Ash	70.66	74.52	75.63	64.69	65.08	65.10
	CP*	29.34	25.48	24.37	35.31	34.92	34.90
	Cpav**		26.40				

	Ash	61.36	67.32	66.21	60.30	60.73	60.05
815	CP*	38.64	32.68	33.79	39.70	39.27	39.95
	Cpav**		35.04			39.64	
	Ash	61.20	67.04	65.89	60.22	60.67	59.95
950	CP*	38.80	32.96	34.11	39.78	39.33	40.05
	Cpav**		35.29			39.72	

**) Combustible part*

***) Combustible part average*

2.3 X-ray diffraction analysis (XRD)

Phase analysis of the two experimental samples was conducted by using an X-ray diffractometer (XRD, Rigaku Ultima IV, Japan), with filtered CuKα1 radiation (λ = 0.154178 nm). X-ray diffraction data were collected over the 2θ range from 10° up to 70° with the step of 0.02° and the scanning rate of 5 °/min. The PDXL2 v2.0.3.0 software with reference to the diffraction patterns available in the International Center for Diffraction Data (ICDD) was used for the phase identification and data analysis [15,16].

Phase analysis of the test materials was performed to reveal their mineralogical composition. For that purpose, the part of test bricks (Figures 3 and 4) were crushed and milled into fine powder form. The obtained mineralogical compositions are presented in Figure 5 (sample 1) and Figure 6 (sample 2). Based on XRD analyses, calcite ($CaCO_3$) and alite (Ca_3SiO_5) were identified as dominant minerals as components of the used cement. The presence of quartz (SiO_2) was observed in a smaller amount (Figure 5). On the other hand, in sample 2 (Figure 6) the peak search analysis identified gypsum, calcium sulfate hydrate $Ca(SO_4)(H_2O)0.5$, calcite ($CaCO_3$), and a small amount of carbon.

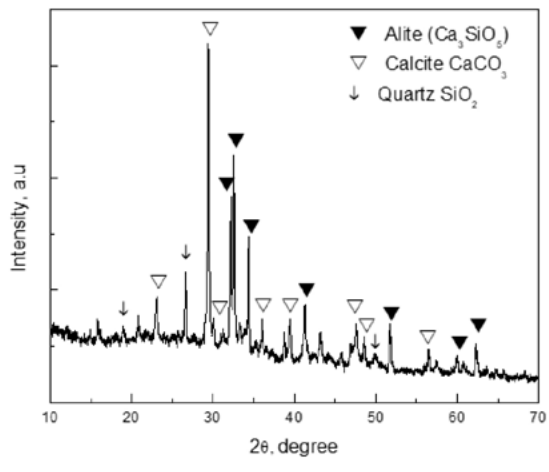

Figure 5. X-ray diffraction pattern of the sample 1.

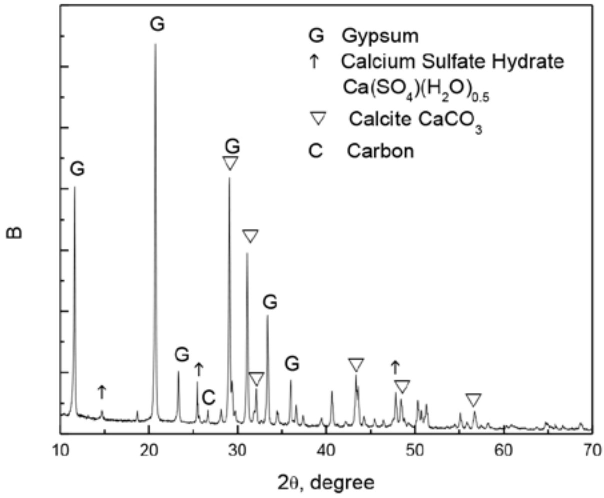

Figure 6. X-ray diffraction pattern of the sample 2.

2.4 Microstructural characterization

Bio-building materials were made of soybean straw by-products mixed with a binder (lime-based, clay, etc.). This leads to a microstructure that is both complex and variable, depending on the many factors. Microstructural characterization of both experimental samples was carried out by an apochromatic stereo microscope (Stemi 508, Zeiss) equipped with a digital camera (Axiocam 212 color, Zeiss). Microscopic observation of building materials provides information on porosity and structure at the microscopic scale (Figures 7 and 8).

The soybean straw fibers are clearly visible in structure (Figure 7a), which are well connected to the homogeneous, basic matrix (Figure 7b).

On the other hand, the microstructure of sample 2 is more complex. In addition to the clearly visible soybean straw fibers (Figure 8a), the two different zones in the base matrix are also observed (Figures 8a, b).

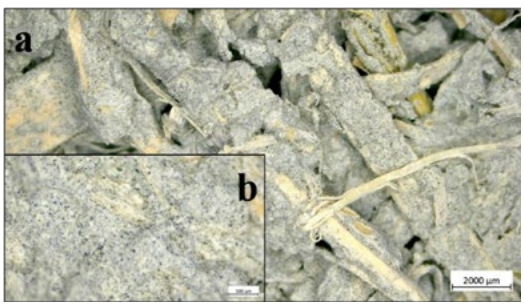

Figure 7. Microstructure (LM) of sample 1 (a) with detail (b).

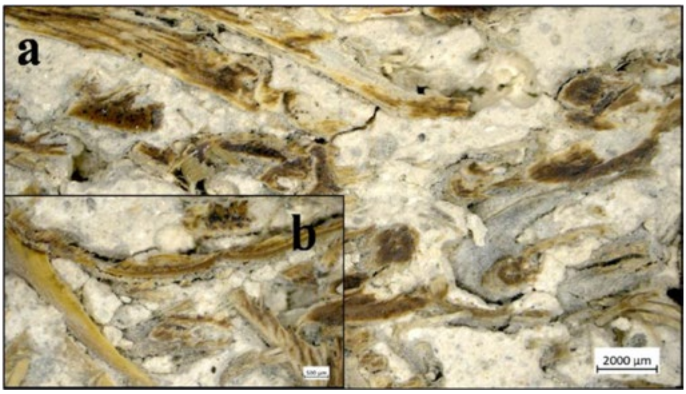

Figure 8. Microstructure (LM) of sample 2 (a) with detail (b).

3. CONCLUSIONS

Research has shown that the use of soybean straw has potential for the production of cement-lime based building materials. The measured values of thermal conductivity and density have shown that by adding straw, a lighter material with a lower thermal conductivity, but with a lower heat capacity, can be obtained, suggesting that a series of extensive measurements of the various properties are required for future application.

First and foremost, it is necessary to determine the influence of the straw content on the thermal and mechanical properties, important for building materials, i.e. how does an increase in the straw content affect the thermal conductivity and specific heat capacity, as well as the compressive and tensile strength. This investigation is also important from the point of view of determining the maximum proportion of straw in the material that does not have a negative impact on the strength of the component. In this context, one of the research directions should relate to the influence of straw size and the composition of the basic binder on the maximum straw content and the homogeneity of the material, as well as on the thermal and mechanical properties.

In addition to the aforementioned investigations, it is necessary to examine the resistance of such materials to fire and noise, as well as the diffusion of water vapour through the material.

Considering that these biomaterials were sourced from a manufacturer who did not disclose the exact composition of the cement matrix and the involvement of soy straw in it, this work opened the door and provided an incentive for further and extensive research on this topic.

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TECHNO-ECONOMIC ANALYSIS OF SOLAR PHOTOVOLTAIC SYSTEM FOR AGRICULTURAL PUMPING IRRIGATION AT NATIONAL ROOT CROP RESEARCH INSTITUTE, ABIA STATE, NIGERIA

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Abstract. This research presents an economic analysis of a 24 kW Solar Photovoltaic (PV) system tailored for sustainable agricultural irrigation. The proposed system comprises 60 high-efficiency solar panels rated at 400 W each, a modular inverter configuration for power conversion, and supporting infrastructure, including mounting structures, piping, and control systems. The system meets a daily energy demand of 60.29 kWh, with operational parameters including 10 hours of daily use and 300 days of annual operation. The economic analysis evaluates capital and operational expenditures, highlighting the long-term cost advantages of the solar PV system over diesel-powered alternatives. The capital cost of the solar system is ₦13,900,000, including ₦6,600,000 for panels, ₦3,000,000 for a modular inverter setup, and other associated infrastructure costs. The Levelized Cost of Energy (LCOE ₦16.57/kWh) and Net Present Value (NPV ₦158,000,000) analyses underscore the system's economic feasibility, with a payback period of approximately 7.2 years. Environmental impact analysis reveals significant carbon savings, with the PV system producing only 48,000 kg of CO_2 emissions over its lifetime compared to 201,000 kg from a diesel system, reducing the environmental burden by over 76%. This study demonstrates that the solar PV irrigation system offers a sustainable solution by reducing energy costs, mitigating carbon emissions, and enhancing agricultural productivity. Recommendations focus on quality installation, scheduled maintenance, and provisions for scalability to adapt to future energy demands, ensuring the system's reliability and alignment with sustainability goals over its 25-year lifespan.

Keywords: Solar photovoltaic energy, Net Present Value (NPV), Payback Period (PP), Levelized Cost of Energy (LCOE), CO_2 emissions.

1. Introduction

In Abia State, Nigeria, agriculture is pivotal in supporting livelihoods and contributing to the regional economy. However, agricultural productivity, especially in the context of crop cultivation, is highly dependent on effective and consistent irrigation practices. The traditional methods of irrigation in the region have been grappling with numerous challenges, primarily due to unreliable electricity supply and the rising costs of operation [1].

Adopting solar-powered irrigation systems could revolutionize agricultural practices in Abia State, enabling farmers to overcome the constraints posed by erratic electricity supply and high operational costs.

Solar photovoltaic (PV) systems operate based on the principle of converting solar energy into electrical energy using semiconducting materials that exhibit the photovoltaic effect [13]. The advancement in solar PV technology has led to increased efficiency and reduced costs, making it an attractive option due to its unlimited and greenhouse gas emission-free nature [14]. The basic principle of solar PV involves directly transforming solar irradiation into electrical energy [13]. This technology has been integrated into various applications, including maritime vessels, buildings, and water pumping systems, showcasing its versatility and potential for widespread use [2].

Agricultural productivity in rural Abia State relies heavily on consistent and sustainable irrigation. The current state of irrigation is hampered by erratic electricity supply and escalating operational costs, posing significant challenges to agricultural yields and sustainability. Many works on farm irrigation have helped in this study. The integration of solar PV with other renewable energy sources, such as solar thermal utilization, has been investigated to optimize energy generation [10]. The continuous reduction in the cost of PV systems due to technological advancements has positioned solar PV as a cost-effective and environmentally friendly energy source for future massive deployment [11]. Developing grid-friendly controls for utility-scale PV power plants has also contributed to grid stability and reliability [4]. Technological advancements have also led to the development of innovative strategies to enhance the performance of solar PV systems. These include optimizing solar electric power generation and demand-side management in buildings and implementing intelligent systems for automatic solar tracking to improve overall system efficiency and cost-effectiveness [6]. Moreover, integrating solar PV with energy-harvesting systems and using big data for cloud operation and maintenance have further expanded the capabilities and potential applications of solar PV technology [12].

Solar PV technology has diverse applications in agricultural settings, offering benefits and challenges. The concept of agrivoltaics, which involves co-developing the same land for both solar PV power and conventional agriculture, has gained attention to address land challenges and minimize water use in water-limited areas [3]. Solar energy has direct applications in agriculture, particularly for water treatment and irrigation, contributing to improved land use efficiency [7]. The integration of solar PV with agriculture, known as photovoltaic agriculture, has the potential to promote the development of both the PV industry and modern agriculture, offering opportunities for colocation and addressing land use conflicts [1]. Solar PV systems have also been utilized for agricultural water pumping, providing a sustainable solution that aligns with the seasonal increase of incoming solar energy [16]. Furthermore, the integration of solar technology into modern greenhouses has been explored, offering potential benefits for agricultural production [15].

Despite the benefits, challenges exist in the widespread adoption of solar PV technology in agriculture. These challenges include economic, institutional, and social barriers and land use conflicts with agricultural production [1]. Additionally, concerns regarding the competition for land between solar energy development and agricultural production need to be addressed, raising questions about the extent of the problem of energy generation versus food production [5]. Furthermore, the economic feasibility and performance of solar power on agricultural land require careful consideration, especially in specific regional contexts [8]

Moreover, the optimization of standalone photovoltaic drip irrigation systems has been investigated, utilizing simulation tools for load and supply optimization, demonstrating the practical application of solar PV in irrigation systems [17]. Additionally, the performance evaluation and optimal sizing of solar water pumping systems have been compared to conventional diesel systems, considering factors such as average monthly solar radiation and water requirements [9]. This study aims to assess the current irrigation practices and energy usage in rural agricultural settings of Abia State, evaluating the cost-effectiveness and sustainability of the proposed solar PV system compared to the traditional irrigation method.

2. Materials and methods

Study area description

The National Root Crops Research Institute (NRCRI) is located at approximately 5.49°N latitude and 7.54°E longitude in Umudike, Abia State, Nigeria. The region's geographical position near the equator results in a tropical climate with significant solar irradiance levels, which is conducive for solar PV applications. The average annual temperature ranges from 25°C to 30°C, with high humidity levels, making it an ideal location for root crop cultivation. The specific climatic conditions, including solar radiation patterns, are crucial for determining the efficiency and design of the solar PV system for irrigation purposes. Refer to Figure 3.1 for a detailed map of the study area.

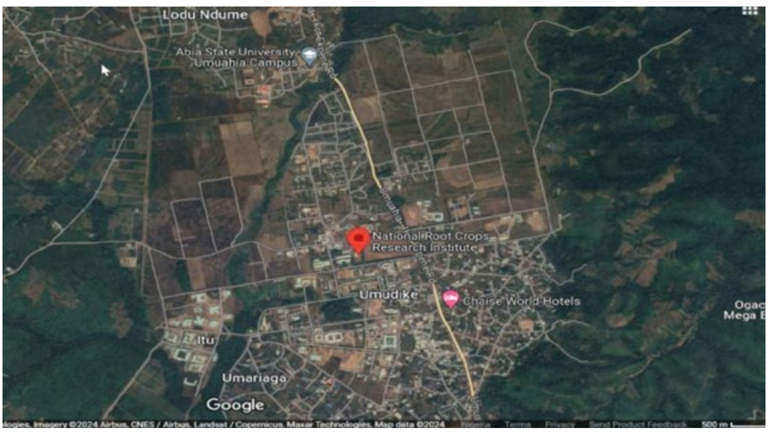

Figure 1. Map showing National Root Crops Research Institute, Umudike

Agricultural Profile

With Umudike as a focal point, Abia State is characterized by a rich agricultural heritage, predominantly in root crop cultivation. The crops primarily include cassava, yams, and sweet potatoes, integral to the local diet and economy. Irrigation needs vary depending on the crop type, growth stage, and seasonal weather conditions. The region's agricultural practices currently rely on traditional methods of irrigation, which are subject to the availability of water and power sources. The introduction of a solar PV system for irrigation has the potential to revolutionize these practices, ensuring a more consistent and sustainable approach to crop cultivation in the area.

Data collection

This data can be sourced from local weather stations and satellite data. The key parameters to be collected include daily solar irradiance, temperature, and humidity levels over a year.

Data Analysis: The collected data will be analysed to understand the area's solar potential. Statistical tools and software such as MATLAB or Python can be employed for data analysis. Time-series analysis will be conducted to discern patterns and variability in solar irradiance and other climatic factors.

Components of the Solar PV System

The solar PV system consists of several key components: solar panels, inverters, controllers, piping, and mounting structures (Table 1). The selection of each component is crucial and depends on factors like local solar irradiance, energy requirements, and budget constraints.

Table 1. Bill of Engineering Materials

Item	Quantity	Unit Cost (NGN)	Total Cost (NGN)	Remarks
Solar Panels (400 W each)	60	₦110,000.00	₦6,600,000.00	Total capacity: 24 kW.
Inverter (24 kW)	1 unit	₦5,500,000.00	₦5,500,000.00	Includes MPPT and grid connection.
Pump (10kW)	1 unit	₦1,500,000.00	₦1,500,000.00	10kW pump for solar
Mounting Structures	1 set	₦1,000,000.00	₦1,000,000.00	Fixed tilt structures.
Piping and Accessories	Lump sum	₦2,500,000.00	₦2,500,000.00	Includes pipe network for irrigation.

Controls and Monitoring	Lump sum	₦800,000.00	₦800,000.00	Controllers and sensors.
Installation and Labour	Lump sum	₦1,000,000.00	₦1,000,000.00	Installation by certified engineers.

Solar PV System Modelling.

The Solar irradiance on the panel's surface is calculated using the equation. (1), according to [1].

$$G=G_{stc}\times(1+\beta\times(T-T_{stc}\ )) \tag{1}$$

Where: (G) is the solar irradiance; \(G_{stc}) is the solar irradiance under standard test conditions; (β) is the temperature coefficient of the panel, (T) is the ambient temperature, and (T_{stc}) Is the temperature under standard test conditions.

The efficiency of a solar panel, (η), is stated by [3], is given by the equation (2):

$$\eta=\eta_{stc}\times(1+\beta_{\eta}\times(T-T_{stc}\ )) \tag{2}$$

where (η_{stc}) is the efficiency at standard test conditions; and (β_{η}) is the efficiency temperature coefficient.

The energy output of the system can be estimated using the equation. (3) as presented by [2].

$$E\ =\ A\ \times G\ \times\eta \tag{3}$$

where (E) is the energy output, (A) is the area of the solar panel, and (G) is the solar radiation

The crop water requirement WIt is calculated as a function of the evapotranspiration rate and the cultivated land area [16]. The relationship is expressed in the equation. (4).

$$W=ET_{c}\times A_{crop} \tag{4}$$

Where: W is the total water requirement for the crops (m^3/day). ET_c represents the crop evapotranspiration rate, which accounts for both soil evaporation and plant transpiration (mm/day); A_{crop} is the total cultivated area (m^2).

The Crop Evapotranspiration (ET_c) The value of ET_c is derived by combining the reference evapotranspiration ET_0 with a crop-specific coefficient K_c that reflects the water needs of the crop throughout its growth cycle. Where ET_0 is determined from local meteorological data, using a simplified estimation model that incorporates solar radiation, temperature, and relative humidity. Adjustments are made for seasonal variability and crop-specific factors. Area of Cultivation (A_{crop}): The cultivated area is based on the dimensions of the farm and crop spacing guidelines.

Energy Consumption of the Irrigation pump according to [16] is given in Eqn. (5).

$$E_p = P_p \times T_p \tag{5}$$

Where E_p is the energy consumption (kWh), P_p Is the pump power (kW), and T_p is the runtime (hours).

Agricultural Data Collection

Irrigation Practices and Crop Data: To understand the irrigation requirements and challenges, data on current irrigation practices, crop water needs, and cultivation patterns were collected through surveys and interviews with the National Root Crops Research Institute (NRCRI). This data provided the basis for identifying the specific water demands and unique needs of crops like cassava, sweet potato, and other commonly cultivated species.

A summary of the crop data, including root depth, growth periods, and average daily water requirements, is presented in Table 2.

Table 2: Crop Water Requirements at NRCRI.

Crop	Root Depth (m)	Growth Period (days)	Daily Water Requirement (mm/day)
Cassava	0.5 - 1.0	240 - 300	4 - 6
Sweet Potato	0.3 - 0.5	120 - 180	3 - 5
Rice farm	0.2-0.1	90 - 160	6-10

To estimate the irrigation needs for each crop, the crop water requirement CWR was calculated using the equation (6) as presented by [15].

$$CWR = ET_c = K_c \cdot ET_o \tag{6}$$

Where:

CWR is the crop water requirement in mm/day; K_c It is the crop coefficient, which varies with the crop's growth stage; ET_o The reference evapotranspiration is in mm/day, calculated using the Penman-Monteith equation.

The Penman-Monteith equation is used to calculate ET_o In eqn. (7).

$$ET_o = \frac{0.408 \cdot \Delta \cdot (R_n - G) + \gamma \cdot \frac{900}{T + 273} \cdot u_2 \cdot (e_s - e_a)}{\Delta + \gamma \cdot (1 + 0.34 \cdot u_2)} \tag{7}$$

Where:

Δ: Slope of the vapor pressure curve ($kPa/°C$); R_n-Net radiation at the crop surface ($MJ/m^2/day$); G-Soil heat flux density (MJ/m^2/day); γ-Psychrometric constant ($kPa/°C$).

T- Mean air temperature (°C); u_2-Wind speed at 2 m height (m/s); e_s-Saturation vapor pressure (kPa); e_a-Actual vapor pressure (kPa).

The economic analysis [5, 8]:

Total System Cost: The total initial investment cost C_"total" was computed in the equation. (8).

$$C_{total} = C_{PV} + C_{inverters} + C_{installation} \tag{8}$$

C_{PV} -Cost of photovoltaic panels; $C_{inverters}$ - Cost of inverters; $C_{installation}$ - Cost of installation (including labour and materials);

The operating Costs-the annual operating cost C_{op} was calculated in the equation. (9)

$$C_{op} = C_{maintenance} + C_{replacement} \tag{9}$$

$C_{maintenance}$ -Annual maintenance cost (estimated as a percentage of total system cost).

$C_{replacement}$ -Cost of replacing components like batteries and inverters during their lifecycle.

Net Present Value (NPV) is stated by [8] in eqn. (10).

$$NPV = \sum_{t=0}^{T} \frac{B_t - C_t}{(1+r)^t} \tag{10}$$

Where:

B_t-Benefits (e.g., savings from reduced diesel consumption) in year t; C_t-Costs in year t; r-Discount rate. T-Project lifetime in years.

Internal Rate of Return (IRR): The IRR was computed iteratively by finding the equation's discount rate (r). (11).

$$(IRR) = \sum_{t=0}^{T} \frac{B_t - C_t}{(1+r)^t} = 0 \tag{11}$$

Payback Period (PP): The payback period was determined by identifying the year in which cumulative benefits equal or exceed cumulative costs, and it is presented in Eqn. (12).

$$(\mathrm{PP}) = \min\{ t \mid \sum_{i=0}^{t} B_i \geq \sum_{i=0}^{t} C_i \} \tag{12}$$

The Levelized Cost of Energy (LCOE) is stated in eqn. (13) as presented by [5,8].

$$LCOE = \frac{\sum_{t=0}^{T} \frac{C_t}{(1+r)^t}}{\sum_{t=0}^{T} \frac{E_t}{(1+r)^t}} \quad (13)$$

Where:
C_t-Total costs in year t; E_t-Energy generated in year t.
Lastly, Table 3 shows all cost inputs used in this research, derived from market surveys conducted in Abia State.

Table 3: Cost Input Data from Field Survey

Component	Solar PV System Cost (NGN)	Diesel System Cost (NGN)	Remarks
Solar Panels | Diesel Generator	₦110,000 per panel (24kW)	₦5,400,000 (20kW)	The model calculates the number of panels based on real-time vendor quotes.
Pump	₦1,500,000	₦1,200,000	10kW pump for solar; standard diesel pump cost.
Mounting Structure	₦1,000,000	₦230,000	Required for solar PV system.
Piping	₦2,500,000	₦2,500,000	Shared cost between solar and diesel systems.
Installation Costs	₦1,000,000	₦500,000	Vendor and Labor costs for installation.
Control Systems	₦800,000	N/A	Exclusive to the solar system.
Total Capital Cost	Varies by inputs	₦4,200,000	The number of solar panels for the PV system depends on
Diesel Fuel Price	N/A	₦1,200 per litre	Market rate per litre of diesel fuel.
Diesel Consumption	N/A	2.5 litres/hour	Fuel usage for a 10-hour daily operation.
Maintenance (Annual% %)	2% of the capital cost	5% of the capital cost	Routine system upkeep percentages.

Fig. 2: Solar pumping system for farmland Irrigation.

3. Results and discussion

Results analysis:

The results of the simulation of a solar photovoltaic (PV) irrigation system designed for a 32.25-hectare farmland in NRCRI Umudike, Abia State (Fig. 3), Nigeria, are presented below. The discussion highlights key observations, comparing simulated performance metrics of the PV system against the requirements for irrigation, and evaluates system viability. The simulation spanned two representative days, accounting for diurnal and seasonal variations in solar irradiance, ambient temperature, and irrigation demand. All results are structured to align with the system's functional objectives and provide insights into operational performance.

Figure 3: 32.25-hectare farmland in NRCRI Umudike

The simulation data:

The simulation used Python and the PVLib library for photovoltaic system modelling. Key constants and assumptions included:

Solar Irradiance and Ambient Temperature: Derived from clear-sky models specific to the Umudike region.

PV System: High-efficiency 400 W panels, totalling 24 kWp (60 panels), operating at an efficiency of 18% under standard test conditions (STC).

Irrigation: Daily water depth requirement of 4 mm across 32.25 hectares, divided into six sections for operational efficiency.

Pump System: A submersible pump operating at 80% efficiency, with a maximum power requirement of 10 kW and safety factors incorporated in dynamic head calculations.

Table 4 shows the system performance during morning hours when solar irradiance is relatively low. The PV output gradually increases, meeting pump demand with minor deficits in the early hours.

Table 4: Morning Results for Days 1 and 2

Time	PV Output (kW)	Pump Demand (kW)	Surplus Energy (kW)	Water Flow (m^3/h)	Active Section	Day
08:00	1.55	2.13	-0.58	21.5	1	1
09:00	2.6	2.13	0.48	21.5	1	1
10:00	3.47	2.13	1.34	21.5	1	1
11:00	4.08	2.13	1.96	21.5	1	1
08:00	1.54	2.13	-0.59	21.5	2	2
09:00	2.6	2.13	0.47	21.5	2	2
10:00	3.46	2.13	1.34	21.5	2	2
11:00	4.08	2.13	1.96	21.5	2	2

The system experienced power deficits at 08:00 on both days, requiring energy storage or operational adjustments.

By 09:00, the PV output met and exceeded the pump demand, ensuring stable water flow.

Table 5: Peak Results for Days 1 and 2

Time	PV Output (kW)	Pump Demand (kW)	Surplus Energy (kW)	Water Flow (m^3/h)	Active Section	Day
12:00	4.41	2.13	2.29	21.5	3	1
13:00	4.43	2.13	2.3	21.5	3	1
14:00	4.14	2.13	2.01	21.5	3	1

15:00	3.55	2.13	1.42	21.5	3	1
12:00	4.41	2.13	2.29	21.5	4	2
13:00	4.43	2.13	2.31	21.5	4	2
14:00	4.14	2.13	2.02	21.5	4	2
15:00	3.56	2.13	1.43	21.5	4	2

The surplus energy during peak hours provides an opportunity to recharge batteries or support additional loads.

The irrigation system operated entirely during these hours, meeting the design requirement.

Discussion of results:

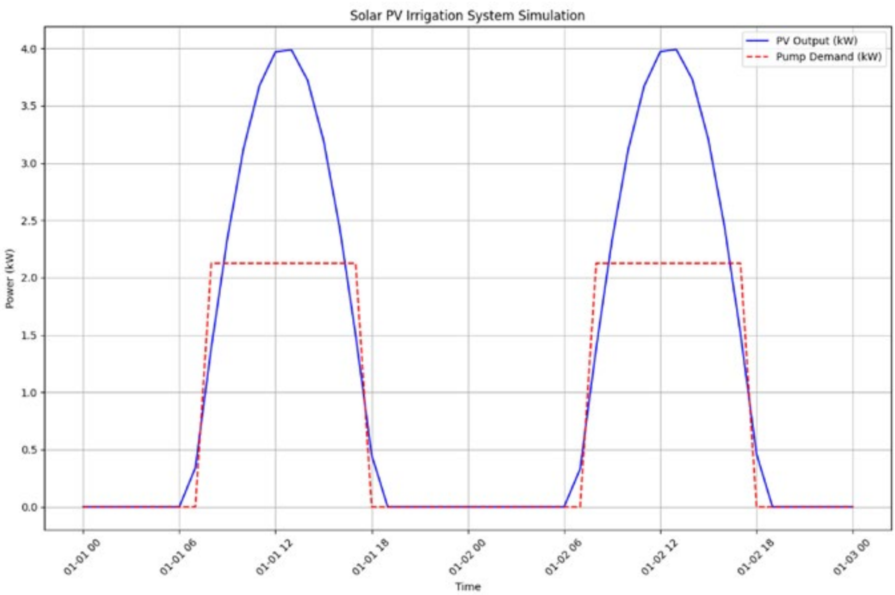

Figure 4: Solar PV Irrigation System Simulation

Fig. 4 illustrates the dynamic behaviour of the solar PV irrigation system under varying conditions throughout the day. The simulation outputs include solar PV energy production, pump energy demand, surplus energy, and water flow rates. Key observations from the figure and supporting data reveal the following:

Energy Balance: The system demonstrates a strong alignment between energy generation and consumption during peak solar hours (12:00–15:00). The energy surplus during these hours is substantial, offering opportunities for energy storage or auxiliary applications. However, in the early morning hours (e.g., 08:00), PV output is insufficient to fully meet the pump demand, leading to negative energy balances. These results are within the range of outcomes in [16, 17]. Water Flow Consistency: Despite fluctuations in energy availability, the irrigation system maintains a steady water flow rate of 21.5 m^3/h across active sections. This reflects the robustness of the system design, ensuring consistent irrigation despite minor energy deficits. The system switches between different active irrigation sections, as indicated by simulation data. This staggered operation ensures that the entire farmland receives adequate water distribution while optimizing energy use.

Implications: These findings validate the capability of the PV irrigation system to perform efficiently under typical solar conditions. However, addressing morning energy deficits through additional storage or optimized irrigation scheduling could enhance performance.

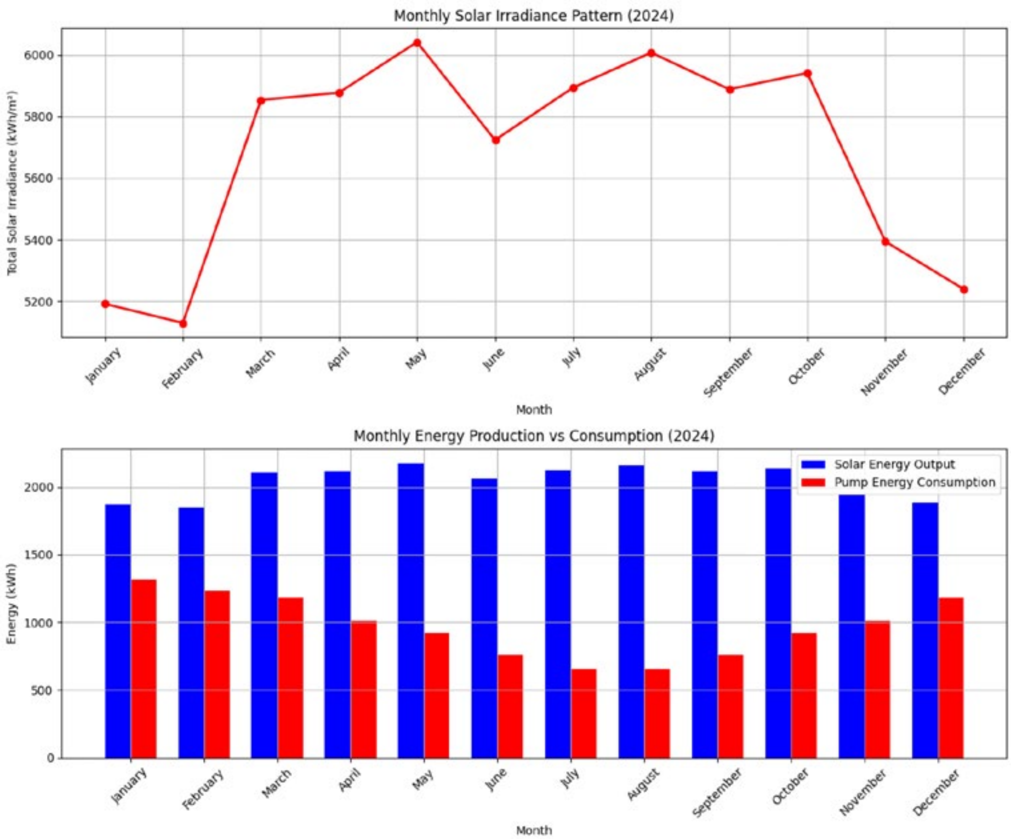

Figure 5: System Monthly Solar Irradiance, Energy Production vs Consumption

Fig. 5 presents a comparative analysis of monthly solar irradiance, energy production, and pump consumption. This section uses the provided data to explore seasonal variations and their impact on system performance.

(1). Solar Irradiance Trends:

The monthly solar irradiance ranges between 5130.01 kWh/m² (February) and 6040.81 kWh/m² (May). The data reveals higher irradiance values from March to October, corresponding to the dry season, and relatively lower values during the wet season (November to February). This trend directly influences the energy production of the PV system.

(2) Energy Production and Consumption:

The energy production varies between 1,846.80 kWh (February) and 2,174.69 kWh (May). Notably, the highest energy output aligns with the peak solar irradiance in May, indicating the effectiveness of the PV array in harnessing solar energy. The Pump energy consumption demonstrates seasonal variations, with higher values during the dry season (e.g., January: 1,318.05 kWh) when irrigation demand is elevated and lower values during the wet season (e.g., July and August: 651.75 kWh). The energy surplus (solar output minus pump consumption) is significant in most months, particularly during periods of low irrigation demand. For example, in July, the surplus reaches approximately 1,469.87 kWh, offering opportunities for storing excess energy or diverting it for other farm operations, as shown by the results of [13, 14,15].

Implications: The seasonal analysis underscores the adaptability of the PV irrigation system to changing climatic conditions. The substantial energy surplus during low-demand months could be utilized to offset deficits during peak irrigation periods, thereby enhancing system sustainability.

Economic and Environmental Benefits of the Solar Photovoltaic System

Economic Benefits: Leaving diesel-powered irrigation for a solar photovoltaic (PV) system presents significant financial advantages. These benefits stem from reduced operating costs, higher returns on investment, and enhanced cash flow sustainability over the system's lifespan, which showed similar results to [9]. Key highlights include:

1. Lower Operating Costs: The solar PV system eliminates the need for diesel fuel, a significant expense in diesel-powered irrigation. For example, while the first-year operating cost for the diesel system is ₦4,424,500, the solar system's maintenance cost is only ₦538,660, resulting in substantial savings from the outset. This cost advantage amplifies over time due to inflation and rising diesel prices.
2. Net Present Value (NPV): The solar PV system delivers a higher NPV of ₦158,000,000 compared to the diesel system. This indicates that solar investment is more profitable over 25 years, even after accounting for the initial capital cost of ₦15,800,000.
3. Payback Period: The solar PV system's payback period is estimated at 7 years, after which it generates consistent financial savings. In contrast, the diesel system's high and escalating operating costs result in a significantly more extended or undefined payback period.
4. Levelized Cost of Energy (LCOE): The LCOE for the solar PV system is ₦16.57/kWh, substantially lower than the diesel system's ₦72.45/kWh. This reflects the solar system's cost efficiency in energy production over its lifespan.

5. Enhanced Crop Revenue: The solar PV system maximizes crop yields by ensuring consistent irrigation with reduced downtime. Annual crop revenues are projected to grow significantly due to inflation-adjusted benefits, further bolstering the system's economic viability.
6. Cumulative Financial Gains: As shown in Figure 5, the cumulative cash flow for the solar system steadily surpasses the diesel system over the years, achieving a marked advantage of over ₦150,000,000 by the end of the system's life. This trend highlights the long-term financial sustainability of solar investments.

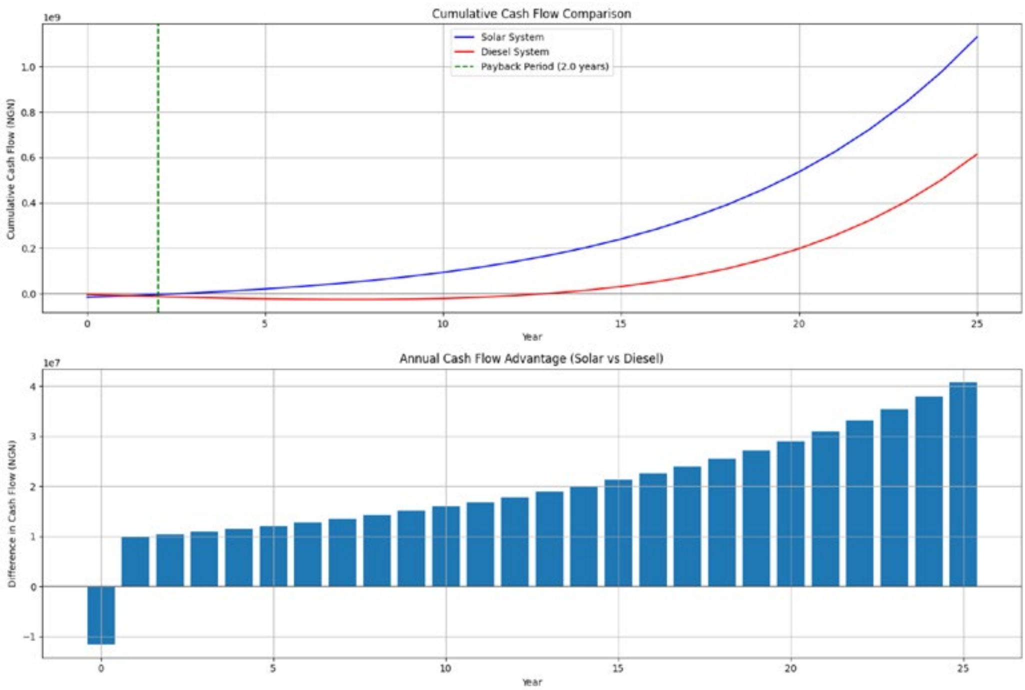

Figure 6: Cumulative Cash Flow Comparison (Solar vs Diesel)

Environmental Benefits: The solar PV system also offers remarkable environmental advantages, positioning it as a sustainable alternative to diesel-powered irrigation, which is in line with the results of [5,8]:

1. Reduction in Carbon Emissions: Diesel systems emit approximately 2.68 kg of CO_2 Per litre of fuel consumed. Over 25 years, the diesel system would generate a total of 201,000 kg of CO_2. In contrast, the solar PV system's lifetime emissions, mainly from manufacturing, amount to 64,000 kg of CO_2 (800 kg per panel for 80 panels), saving 137,000 kg of CO_2 Emissions.
2. Mitigation of Fossil Fuel Dependence: By transitioning to solar, the system reduces reliance on fossil fuels, helping to stabilize local energy demand and reduce the en-

vironmental degradation associated with diesel production and transportation.

3. Support for Sustainable Agriculture: Solar-powered irrigation aligns with global sustainability goals by fostering eco-friendly agricultural practices. This contributes to soil preservation, water management, and overall environmental health.
4. Enhanced Air Quality: Diesel engines emit not only CO_2 However, particulate matter, sulfur oxides (SOx), and nitrogen (NOx) also contribute to air pollution. Solar systems avoid these emissions, promoting cleaner air in agricultural communities.

Conclusion

The proposed solar photovoltaic (PV) system is a sustainable and cost-effective solution for the project's energy needs. With a total installed capacity of 24 kW, the system is designed to ensure a reliable energy supply while reducing dependency on conventional energy sources. Including high-efficiency solar panels, a state-of-the-art inverter, and robust mounting structures guarantees optimal performance and durability. This system aligns with global trends toward renewable energy adoption and contributes to environmental sustainability by significantly reducing carbon emissions. The design also supports efficient irrigation, which enhances agricultural productivity and ensures the project's long-term viability. The economic analysis evaluates capital and operational expenditures, highlighting the long-term cost advantages of the solar PV system over diesel-powered alternatives. The capital cost of the solar system is ₦13,900,000, including ₦6,600,000 for panels, ₦3,000,000 for a modular inverter setup, and other associated infrastructure costs. The Levelized Cost of Energy (LCOE ₦16.57/kWh) and Net Present Value (NPV ₦158,000,000) analyses underscore the system's economic feasibility, with a payback period of approximately 7.2 years. Environmental impact analysis reveals significant carbon savings, with the PV system producing only 48,000 kg of CO′ emissions over its lifetime compared to 201,000 kg from a diesel system, reducing the environmental burden by over 76%. The cost analysis indicates that the system is economically feasible, with an initial investment of ₦13,900,000. Over its operational lifespan of 25 years, the system promises substantial savings on energy costs while delivering environmental benefits. The economic and ecological advantages of the solar PV system over diesel irrigation are evident in reduced costs, greater financial returns, and significant. CO_2 Savings. By harnessing clean energy, the solar system supports sustainable development and provides a model for environmentally responsible irrigation in similar contexts. Fig. 6 illustrates the long-term economic benefits, reinforcing the case for solar PV systems as a viable and sustainable solution.

Recommendations

1. Implementation: Install the proposed Solar PV system as it efficiently meets the energy and operational requirements.
2. Quality Assurance: Ensure that all materials, including solar panels, inverters, and mounting structures, are sourced from reputable manufacturers to guarantee performance and durability.

3. Professional Installation: Engage certified engineers to install and commission the system to ensure best practices and standards compliance.
4. Maintenance Plan: Develop and implement a schedule to ensure optimal system performance and longevity.
5. Scalability: Consider scaling the system in the future if energy demands increase, leveraging the modular nature of solar PV systems.
6. Monitoring and Evaluation: Deploy a monitoring system to track energy generation, consumption, and system efficiency, enabling informed decision-making for any necessary upgrades or adjustments.

With these recommendations in place, the Solar PV system will serve as a reliable, sustainable, cost-effective energy solution for the project.

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GLOBAL TRENDS OF DIGITAL TRANSFORMATION OF AGRICULTURE AND THEIR PROJECTION ON RUSSIA

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Abstract. The authors conducted a bibliometric analysis of scientific publications (databases Elsevier, Google Scholar, MDPI, OpenAlex), on the basis of which a list of priority digital technologies for agriculture was formed. For this, the API service tools and Vosviewer were used). The leading countries in research in the field of digital transformation of agriculture have been identified. The analysis of keywords and annotations of scientific publications made it possible to identify the most common digital technologies, i.e. These are the areas of research that are the most popular among researchers around the world. Their demand determines the critical importance of technology for agriculture. The identified research areas (emerging technologies) and those areas that have already received sufficient distribution have been identified. The resulting list was correlated with the priority areas of scientific and technological development and the list of the most important high-tech technologies of the Russian Federation. 8 groups of research trends in the field of digital transformation of agriculture have been formed. The first is technologies for increasing the productivity of farm animals and their resistance to diseases. This group includes bioinformatics and genetic engineering, biometrics and animal health monitoring, digital genetics, digital biodiversity conservation technologies, and CRISPR/Cas9 genome editing technology. Second, technologies for the development of new-generation veterinary medicines. These are high-performance parallel modeling of molecular interactions and biochemical reactions, machine learning algorithms for predicting drug interactions with animal receptors and enzymes, bioengineered design and printing, and the creation of targeted drugs based on the study of DNA and RNA sequences. Third, technologies for obtaining new varieties and hybrids of plants that are resistant to environmental changes. These include: high-performance genome sequencing, modeling and virtual breeding, technologies of transgenesis and gene transfer, methods of high-performance phenotyping, blockchain to confirm the authenticity and safety of genetic material. Fourth: microelectronics and photonics technologies for information storage, processing, transmission and protection systems: agricultural IoT sensors, telecommunication systems for transmitting data from fields and farms to processing and control centers, digital platforms for collecting, storing and analyzing data on agricultural processes, secure cryptographic protocols for transmitting sensitive information about the earth, plants and animals, blockchain platforms for confirming the origin of products, compliance with norms and regulations in agriculture, radiometric systems for monitoring soil and plants, integrated systems for protecting agricultural IT infrastructure from cyber threats and fraud, intelligent agricultural data analysis systems, biosensors for monitoring plants and animals. Fifth: technologies for creating trusted and secure system and application software. These are artificial intelligence for agroanalytics and forecasting, predictive modeling of crop yields and conditions, software engineering for the development of agricultural applications, computer vision for monitoring plants and animals, advanced analytics and BI-systems for agribusiness, decision support systems (DSS) in agriculture, generative algorithms for modeling agroecosystems, geostatistics and spatial statistics for agricultural mapping. Sixth: transportation technologies for various fields of application: autonomous machines for harvesting, mowing grass, transporting products and fertilizers, as well as intelligent units for spreading seeds and fertilizers, electrical equipment and electric agricultural vehicles. Seventh: space instrumentation technologies for the development of modern communication systems, navigation and remote sensing of the Earth. These are remote sensing and satellite imagery of agricultural territories, geoinformation systems for planning and managing agricultural landscapes, choosing optimal technologies and equipment, digital soil mapping and fertility modeling, Satellite navigation systems for precision agriculture (GPS, GLONASS). Eighth: monitoring and forecasting of the environment and climate change: hydrometeorological systems for agriculture, emergency risk assessment systems and environmental protection measures in agriculture, information systems for water management in agriculture, methods of mapping and analysis of soils, analysis of their composition and mechanical properties, creation of monitoring systems and recommendations for improving fertility and restoration of depleted soils, big data analysis technologies and GIS technologies for agro-climatic forecasting.

Keywords: priority technologies, critical technologies, digital transformation, forecasting, bibliometric analysis.

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1. Introduction

The contemporary agri-food sector is undergoing a profound transformation, driven by the urgent need to enhance productivity, ensure sustainability, and address global food security challenges. This transformation is catalyzed by the rapid development and integration of digital technologies, which are fundamentally reshaping traditional agricultural practices. The concept of "digital agriculture" encompasses a wide array of technologies, including artificial intelligence (AI), the Internet of Things (IoT), blockchain, remote sensing, and big data analytics, which together create intelligent, data-driven farming systems [1].

Identifying and forecasting the development of priority and critical technologies is a strategic task for national economies and scientific communities. It allows for the concentration of resources on the most promising areas, ensuring technological sovereignty and competitive advantage. Bibliometric analysis, as a method of analyzing large arrays of scientific publications, provides an objective tool for identifying research trends, assessing the maturity of technologies, and mapping the global scientific landscape.

This study aims to conduct a comprehensive bibliometric analysis of scientific publications to identify the most relevant and rapidly developing digital technologies in the agri-food sector. The objectives of the research are: to quantify the representation of various technological domains in global scientific literature; to identify interconnections and synergies between different technology groups; and to classify the identified trends within the framework of existing critical technology lists.

2. Materials and methods

The research was conducted using a bibliometric analysis methodology. Two major scientific databases were chosen as data sources: Elsevier's Scopus database and the open-source OpenAlex database. The choice of these platforms ensured a comprehensive coverage of both high-impact journal articles (Scopus) and a broader range of publications including conferences and preprints (OpenAlex).

The data collection period covered 2024-2025 to capture the most recent trends. The search query was built using a set of keywords and their combinations, reflecting the main categories of digital technologies in agriculture: ("digital agriculture" OR "smart agriculture" OR "precision agriculture" OR "Agri 4.0") AND ("AI" OR "IoT" OR "blockchain" OR "big data" OR "remote sensing" OR "autonom" OR "robot*").

The obtained dataset was cleaned and processed using specialized software for bibliometric analysis (e.g., VOSviewer, Bibliometrix in R). The analysis included:

1. Frequency analysis: Calculation of the occurrence frequency of specific technologies and topics.
2. Co-word analysis: Identification of networks of keywords that frequently appear together, revealing the structure of the research field.
3. Cluster analysis: Grouping of technologies into thematic clusters based on the strength of their bibliographic links.
4. Trend analysis: Assessment of the dynamics of publication activity for different technologies over time.

The results of the bibliometric analysis were then systematically mapped onto the official list of critical technologies, allowing for their categorization and prioritization.

3. Results and discussion

Figure 1 presents the results of a frequency analysis of keywords from publications in the Elsevier database for the period 2024-2025, reflecting the structure of scientific interests in the field of digital technologies for agriculture [2]. The size of each segment of the chart is proportional to the share of publications dedicated to the corresponding thematic group. The visualization clearly demonstrates the relative significance of various technological directions identified during the cluster analysis. As evident from the diagram, the largest segment comprises research in “Smart Agriculture and Artificial Intelligence,” highlighting the dominance of this comprehensive approach in the modern scientific agenda. This chart provides the foundation for the subsequent detailed discussion on the priorities and interconnections between the technological clusters.

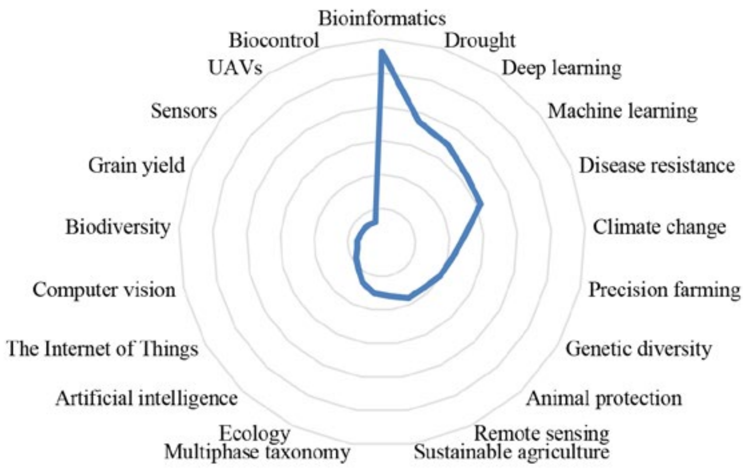

Figure 1. Distribution of research topics related to digital technologies in agriculture (Elsevier database).

An analysis of the publications in OpenAlex showed the following distribution of research in the field of digital technologies in agriculture [3].

Table 1. Distribution of publications in the field of digital technologies in the agro-industrial complex at OpenAlex

Digital Technology Groups	Share of publications
Smart agriculture and AI, smart agriculture	5,75%
Remote sensing in agriculture, Big Data, spectroscopy, soil geostatistics, GPS, Data mining	3,47%
Iot and Edge/Fog Computing, IOT-based systems, advanced sensors, water monitoring	0,77%
Blockchain Applications, Food Supply Chain Traceability	1,18%
AI, Machine Learning, Computer Vision, Image Classification	0,29%

Digital Platforms, E-commerce, Digital Marketing, Sharing Economy	2,37%
Digitalization in Agriculture, ICT Impact, Digital Transformation	8,20%

An analysis of research publication data reveals distinct priorities in the study of digital technologies for the agri-food sector. The domain of "Smart Agriculture and AI" emerges as the predominant area of focus, accounting for 5.75% of all publications examined. This represents not merely a specific technology but a comprehensive paradigm that integrates various digital solutions to create automated farm management systems.

The foundation for these systems is built upon technologies for data acquisition and analytics. Remote sensing and big data constitute the second most significant cluster of research. Satellite imagery and soil geostatistics enable crop monitoring and precise resource assessment, forming the cornerstone of precision agriculture methodologies.

The Internet of Things (IoT) and blockchain are identified as critical enabling technologies. IoT sensors act as the peripheral nervous system of the agri-food complex, facilitating real-time data collection on soil moisture, greenhouse microclimates, and machinery status. Blockchain technology addresses the critical challenge of supply chain traceability, ensuring data integrity and transparency from production to point of sale, thereby enhancing food safety and consumer trust.

While artificial intelligence (AI) is less frequently isolated as a primary research topic, it functions as the central cognitive engine powering the digital transformation. Machine learning algorithms are the underlying force for analyzing remote sensing data, predicting yields, and enabling robotic automation, though this role is often embedded within broader application-focused studies.

Significant research is also directed toward digital platforms and e-commerce, which are transforming economic models within the sector. These technologies provide producers with direct market access and innovative financing tools, thereby altering traditional value chains.

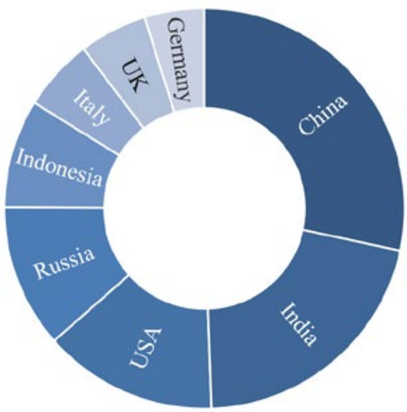

Figure 2. Leading countries in digital agriculture publications

Analysis of the diagram showing the distribution of leading countries by publications in the field of digital technologies for the agro-industrial complex allows us to draw the following key conclusions:

China's Unconditional Dominance. China demonstrates absolute leadership, significantly outpacing all other countries. This is a result of targeted state policy, major investments in R&D, as well as a powerful technological base and a large internal need to ensure food security for its huge population.

Strong Positions of the USA and Western Europe. Traditional scientific powers – the USA, Germany, the UK, Italy – maintain strong positions in the top ten. This indicates their developed academic ecosystem, a strong private ag-tech sector, and long-standing research traditions in precision agriculture. Their research is often focused on high-tech and capital-intensive solutions (robotics, advanced analytics).

Active Involvement of Developing Economies. The high positions of India and Indonesia point to a crucial global trend: the digitalization of agriculture is becoming a critical factor for rapidly developing countries with a large agricultural sector and growing populations. For these countries, the motivation is the need to drastically increase productivity and efficiency to ensure their own food security.

Russia's Positioning. Russia's presence among the leading research countries confirms its competitive advantages and significant scientific-technological groundwork in the digitalization of the agro-industrial complex. This is a consequence of a strong academic school, historical developments in agriscience, and targeted government initiatives in recent years to support the ag-tech direction [4].

Unlike countries focused on mass production, Russian research often demonstrates unique specialization, focusing on solutions for risky agriculture, resilience to climate stresses, and import substitution of critical technologies. This creates niche leadership and potential for exporting specifically adaptive and resilient agri-technologies.

Russia possesses strong potential to transform from a participant into one of the key players on the global ag-tech stage. The unique combination of vast agricultural territories, competencies in fundamental sciences (mathematics, physics, programming), and growing potential in applied development creates ideal conditions for creating end-to-end technological solutions "from field to data" and testing them in real-world conditions [5].

Thus, Russia is not just present in the rankings but has all the necessary prerequisites – scientific, territorial, and technological – to become one of the world's hubs for the development and testing of digital solutions for sustainable and efficient future agriculture.

A bipolar structure of global leadership has emerged. On one side is China as the undisputed leader, and on the other is the collective West (the USA and EU) as the center of fundamental research and development of "high-tech premium" solutions. Simultaneously, the "Global South" (India, Indonesia, Brazil, etc.) is actively gaining weight, for whom digital technologies in the agro-industrial complex are not a luxury but a tool for survival and economic development. In this emerging bipolar architecture, Russia has the opportunity to occupy a unique niche as a technological bridge and a testing ground for stress-resistant and adaptive agri-technologies, capable of providing solutions both for the developed markets of the West and the specific challenges of the Global South. This creates a tense competitive environment and shapes different national models for the implementation of agri-technologies.

The identified bibliometric trends were successfully mapped and integrated into the system of Russia's critical technologies, as shown in Table 2 [6, 7]. This mapping demonstrates how fundamental research feeds into applied critical domains.

The analysis shows that:

Critical Technology 7 is directly supported by advances in bioinformatics, digital genetics, and genomics identified in the bibliometric analysis.

Critical Technology 8 is almost entirely reliant on the digital trends we identified, including AI, computer vision, digital twins, and VR/AR.

Critical Technology 11 provides the fundamental hardware and infrastructure (IoT, sensors, secure data transmission) without which the digital transformation of agriculture is impossible.

Critical Technology 13 represents the software and algorithmic core (AI, ML, predictive modeling) that processes data and creates intelligent systems.

Critical Technologies 14, 15, and 19 are application domains that consume and utilize the digital technologies listed above for specific tasks in transport, space monitoring, and environmental forecasting.

This synthesis reveals that the digital transformation of the agri-food sector is not a collection of discrete technologies but a deeply integrated ecosystem. Research in basic digital domains (AI, IoT, data analytics) directly enables the development of applied critical technologies for agriculture, veterinary medicine, and environmental management.

Table 2. Distribution of research topics by critical technology groups [7]

Critical technology groups	Name of the critical technology	Research topics
Critical technology 7	Technologies for Enhancing Productivity (Including Through Breeding) and Disease Resistance in Livestock	1.Bioinformatics and genetic engineering (e.g., establishing a database of genetic sequences from highly productive animals resistant to specific diseases). 2. Biometrics and animal health monitoring. 3. Digital genetics (e.g., databases of genetic markers). 4. Genetic testing and genome sequencing. 5. Digital technologies for biodiversity conservation (e.g., genetic banks preserving DNA of rare animal and plant species for future restoration).

Critical technology 8	Technologies for the Development of Next-Generation Veterinary Pharmaceuticals, Including for the Prevention and Treatment of Infectious Diseases in Livestock	1. Bioengineering design and printing (e.g., creating 3D-printed models of animal tissues and organs for testing new pharmaceuticals and their delivery methods). 2. Virtual and Augmented Reality (VR/AR) (e.g., programs for training veterinarians and pharmacists in working with new drugs, studying side effects and complications, and visualizing the progression of infectious diseases). 3. Computer vision and artificial intelligence in microscopic analysis (automation of tissue and body fluid sample analysis, early detection of bacteria and viruses). 4. Digital twins (virtual copies of an animal's body used for testing pharmaceuticals). 5. Cluster analysis and machine forecasting (identifying patterns and correlations between disease symptoms, medications, and clinical outcomes). 6. Genomics and bioinformatics (developing targeted drugs based on the study of DNA and RNA sequences). 7. High-throughput parallel modeling of molecular interactions and biochemical reactions. 8. Machine learning algorithms for predicting the interaction of drug substances with animal receptors and enzymes.
Critical technology 11	Microelectronics and Photonics Technologies for Information Storage, Processing, Transmission, and Protection Systems	1. Internet of Things (IoT) 2. Telecommunications 3. Digital platforms 4. Electronic databases 5. Data storage 6. Secure data transmission systems 7. Blockchain 8. Telematics 9. Radiometric approaches 10. Optoelectronic measurements

		11. Library science and informatics 12. Electrical engineering and measuring instruments 13. Cybersecurity 14. Geoinformatics 15. Knowledge representation and processing 16. Real-time distributed systems 17. Signal processing 18. Power grid energy management 19. Geometric optics 20. Electrical equipment and electric vehicles 21. Biosensors 22. Wireless technologies
Critical technology 13	Technologies for Creating Trusted and Secure System and Application Software, Including for Managing Socially and Economically Significant Systems	1. Artificial Intelligence 2. Deep Learning 3. Machine Learning 4. Predictive modeling 5. Decision support systems 6. Advanced analytics 7. Generative algorithms 8. Computer vision 9. Geostatistics and spatial statistics 10. AI and Machine Learning 11. Software engineering 12. Computer vision and graphics 13. Robotics 14. Automation and control systems 15. Knowledge representation and processing 16. Environmental sensing and analysis. 17. Statistics and data analysis 18. Logistics and supply chain management 19. Distance learning and research 20. Semiconductor electronics 21. Electrical measuring instruments 22. Legislation and jurisprudence 23. Sustainable development
Critical technology 14	Transport Technologies for Various Applications (Marine, Land, Air), Including Unmanned and Autonomous Systems	1.Unmanned Aerial Vehicles (UAVs)/ Drones 2.Robotics 3.Electrical equipment and electric vehicles

Critical technology 15	Space Instrumentation Technologies for Developing Modern Communication, Navigation, and Earth Remote Sensing Systems	1. Geographic Information Systems (GIS) 2. Digital soil mapping 3. Remote sensing 4. Satellite technologies 5. Cartographic modeling (e.g., water cover maps) 6. Environmental sensing and analysis 7. Geoinformatics
Critical technology 19	Monitoring and Forecasting of Environmental and Climate Change (Including Key Areas of the World Ocean, Russian Seas, the Arctic, and Antarctic), Technologies for Warning and Mitigating Risks of Natural and Man-Made Emergencies and Their Negative Socio-Economic Consequences	1. Remote data analysis 2. Remote sensing 3. Environmental sensing and analysis 4. Climate change 5. Hydrology and meteorology 6. Ecology and environmental conservation 7. Environmental remediation 8. Water resources 9. Soil science 10. Alternative energy 11. Power systems and energy technologies 12. Renewable energy sources 13. Friction and vibration 14. Seismic risk assessment 15.Disaster mitigation

Analysis of the dynamics and interrelationships of research topics makes it possible not only to ascertain current priorities but also to forecast future development trajectories by identifying three key stages of the technology lifecycle:

1. Technologies transitioning to maturity and routinization (reaching growth plateau). This category includes fundamental data collection technologies such as GPS positioning and basic Geographic Information Systems (GIS). They are no longer standalone subjects of breakthrough research but are considered standard, mandatory infrastructure (“commodity”), integrated into more complex platforms. Their development is focused on optimizing cost, reliability, and usability rather than fundamental innovation.
2. Key research fronts (active growth phase). This is the core of the modern digital transformation of the agri-food sector, demonstrating the highest volume and dynamics of publication activity. This cluster includes:

- precision agriculture based on remote sensing data (multi-/hyperspectral imaging, drones);
- advanced analytics and artificial intelligence (machine learning for yield prediction, diagnostics of plant and animal diseases, computer vision);

- Internet of Things (IoT) and robotics (autonomous agricultural machinery, systems for precision resource application);
- blockchain for ensuring supply chain traceability.

This is where the maximum synergy and interdisciplinarity are observed, indicating their transformative potential for the industry within the next 5-7 years.

3. Emerging and prospective technologies (nascent phase). Bibliometric analysis reveals areas where publication activity is currently low but demonstrates exponential growth and high potential significance. These directions are shaping the future agenda:

- digital Twins of the entire agro-ecosystem (field, farm, animal) for predictive modeling and decision-making in a virtual environment;
- application of generative AI for designing new chemical compounds (pesticides, fertilizers), breeding, and managing the selection process;
- integration of AI with robotics for performing complex operations (e.g., selective fruit harvesting, precision weeding);
- advanced bioinformatics and genomics for creating personalized feed and veterinary pharmaceuticals, which directly correlates with Critical Technology 7 and 8;
- technologies at the intersection of food and digital sciences (e.g., 3D food printing, alternative proteins with digitally controlled quality parameters) [8, 9].

Future breakthroughs are expected not in the realm of individual technologies, but at the intersections of the mentioned clusters, particularly in the convergence of artificial intelligence, robotics, and biotech.

4. Conclusion

The conducted research has enabled a systematic identification and structuring of key global trends in the digital transformation of agriculture and an assessment of their projection onto the scientific and technological development of Russia's agro-industrial complex. Bibliometric analysis of international publications confirmed the dynamic nature of the AgriTech sector's development and the formation of a new technological paradigm based on the convergence of digital, biological, and engineering sciences.

As a result of the study, eight interconnected technology groups defining the landscape of modern digital agriculture were identified: from genomic and veterinary biotechnologies to autonomous machinery, satellite monitoring, and climate risk forecasting systems. It was established that the most intensively developing directions are technologies at the intersection of artificial intelligence, big data, and the Internet of Things (IoT), reflecting a general trend towards creating intelligent, autonomous, and data-oriented agroecosystems.

An important outcome of the work is the alignment of global trends with Russia's national priorities for scientific and technological development. It has been demonstrated that the country possesses significant scientific groundwork and unique competencies, enabling it not only to adapt global developments but also to create competitive solutions focused on specific challenges—such as agriculture in risk-prone zones, import substitution of critical technologies, and ensuring food sovereignty.

Based on the bibliometric analysis, the following overarching global trends can be formulated:

1. From Precision to Predictive Agriculture: The focus is shifting from collecting and analyzing data to predictive modeling using AI, enabling proactive decision-making and risk management.
2. Deep Technological Convergence: The boundaries between digital (AI, IoT), biological (genomics, bioinformatics), and engineering (robotics, drones) technologies are blurring, creating synergistic effects and entirely new solutions.
3. Full-Supply-Chain Integration: Digitalization is expanding beyond the field to encompass the entire agri-food value chain, from input logistics and production to traceability, distribution, and consumer engagement via e-platforms and blockchain.
4. The Rise of the "Agri-Intelligence" Ecosystem: Agriculture is becoming a data-driven industry where the core value is created by intelligent software and analytics services operating on hardware (sensors, machines) and infrastructure (cloud, connectivity).
5. Geopolitical Diversification of Innovation: While China and the West lead in volume and fundamental research, respectively, emerging economies are becoming significant and highly motivated players, driving demand for cost-effective and adaptive technological solutions.

Prospects for further research lie in a deeper analysis of the commercialization and scaling of the identified technological directions, as well as in the development of comprehensive state support measures aimed at stimulating cooperation between scientific organizations, businesses, and the real sector of the agro-industrial complex. The implementation of the presented list of critical technologies within the framework of national agricultural policy will contribute not only to increasing the productivity and economic efficiency of the industry but also to strengthening Russia's position on the global stage as a supplier of technologically advanced and sustainable solutions for the agriculture of the future.

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CERTIFIED MOUNTAIN PRODUCT – QUALITY LABELING IN THE MOUNTAIN ECONOMY

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Abstract. The "mountain product" label is an important quality certification tool, with major potential in supporting the sustainable development of mountain areas in Romania and the European Union. This certification capitalizes on the geographical and cultural specificity of mountain regions, giving products a distinct, authentic and competitive identity. Mountain food products are made from local raw materials, cultivated or obtained in mountain areas located at altitudes of over 600 meters, using traditional and sustainable methods that comply with quality, food safety and environmental protection standards. By promoting these products, certification contributes not only to increasing added value, but also to strengthening the position of farmers on the market, in an economic context in which small producers face numerous difficulties: lack of information, excessive bureaucracy, limited access to financing and poorly developed infrastructure. The "mountain product" label offers a competitive advantage by guaranteeing consumers traceability, clear origin and ecological production methods, elements increasingly appreciated in a market where demand for healthy and authentic products is growing. Certified mountain products are not only quality foods, but also true expressions of local cultural identity. They support the economic and social development of mountain areas by generating income, creating jobs and attracting tourists through gastronomic tourism. Moreover, they contribute to the conservation of biodiversity and the promotion of sustainable agricultural practices, being aligned with the principles of the circular economy. Also, due to their high nutritional value and authentic taste, mountain products can become a healthy and responsible alternative for consumers interested in a balanced lifestyle. The certification of mountain products is a rigorous process, clearly regulated both at national and European level, and includes several key stages: submission of the application, verification of compliance with standards, on-site inspections, laboratory analyses and continuous monitoring. This approach is coordinated by the competent authorities and ensures that only products that meet all the required criteria can benefit from the "mountain product" label. There may also be additional certifications, such as Protected Designation of Origin (PDO), Protected Geographical Indication (PGI), organic certification or the ISO 22000 standard, which increase consumer confidence. The quality indicators of these products refer to precise geographical origin, the application of traditional production methods, the use of high-quality local ingredients, respect for the environment, compliance with rigorous food safety tests and a high nutritional content. Mountain products are produced in limited quantities and are seasonal, which gives them an exclusive character and an authentic connection to local traditions. The National Register of Mountain Products, managed by the Ministry of Agriculture and Rural Development, has the role of centralizing and promoting these products. Although the number of registered products is increasing, the success of the scheme is still limited by administrative challenges and low awareness. To fully harness the potential of this label, it is necessary to simplify procedures, provide financial support and advice for producers, as well as promote a participatory governance model that involves public, private actors and local communities.

Keywords: mountain product, certification, labeling, rural development

Introduction

In recent years, the topic of sustainable development of mountain areas has gained increasing importance in agri-food economic research, due to the vulnerability of these territories and their essential contribution to the conservation of biodiversity, natural resources and cultural heritage (FAO,2021). Certified mountain food products are essential tools for capitalizing on local resources, supporting farmers economically and financially and ensuring competitiveness on the market. The literature frequently addresses the issue of mechanisms for transmitting information to consumers, as provided for in Regulation (EU) No. 1151/2012, and reducing market asymmetries (Regulation EU No 1151/2012; Grunert, 2005).

Some studies show that certified products are perceived by consumers as having high added value and contribute to creating brand loyalty (Belletti, Marescotti & Touzard, 2017; Aprile, Caputo & Nayga, 2012). However, other research claims that the level of knowledge of these products is low, which limits the impact of trust in the institutions responsible for certification. Regarding consumer motivations, the literature highlights both functional reasons such as food safety and nutritional quality, as well as symbolic motivations such as supporting the local community or ethical motivations related to tradition (Cei, Defrancesco & Stefani,2018).

The different perspectives in the literature highlight the importance of in-depth studies that analyze the impact of the “mountain product” label on farmers, especially in terms of its economic and social implications. In this paper, we aim to analyze the role of the “mountain product” label as a quality certification tool in the economy of mountain areas, focusing on the direct effects on the activity of producers. The main hypothesis of the study is that the label has a positive impact on farmers, contributing to increasing the added value of products, strengthening their position on the market and supporting sustainable development in mountain communities. At the same time, the paper takes into account the relatively low level of information regarding the certification process, as well as the reluctance shown by some producers, generated by administrative barriers, perceived high costs or lack of confidence in the real benefits of the label.

1. Definition of the mountain product and the conceptual framework

1.1. The mountain product

Mountain products can be defined as products intended for human consumption, obtained from raw materials from the mountain area, which offer consumers the opportunity to consume healthy foods, originating from an area with low pollution, where extensive, sustainable agriculture is mainly practiced, in balance with the environment. Mountain food products are recognized for their superior quality, authentic taste and close connection with the natural resources of mountain regions. They respect local traditions and are distinguished by a series of specific characteristics. The ingredients used in the production process are of local origin, being cultivated and collected in a traditional way. They are natural, unprocessed and do not contain added additives or preservatives.

The production process of these products follows traditional methods, using recipes passed down from generation to generation, which gives the food a unique identity. Each geographical region in Romania has its own specific mountain food products. These include dairy products made from cow, goat or sheep's milk, such as Telemeaua de Ibănești, Cașul or Brânza de burduf. Homemade sausages, ham or bacon are also made from meat, all smoked and/or dried using traditional methods. Products made from mountain plants also have a special taste, such as blueberry, blackberry or raspberry jams and preserves, honey and natural syrups. The absence of additives and intensive processing contributes to preserving the authentic and intense flavor of meat and dairy products. At the same time, the lack of industrial processing favors the preservation of nutrients unaltered, making these products perceived as healthier compared to those processed and artificially preserved. Mountain food production is closely linked to the principles of sustainability, as the technologies used in preparation do not negatively affect the environment. In addition to traditional methods, producers can also adopt ecological practices in growing plants or raising animals, thus contributing to the protection of mountain ecosystems.

1.2. Peculiarities of mountain production

Raising animals on natural alpine and mountain pastures is a fundamental practice in mountain food production, as their food comes from unpolluted wild plants and herbs, rich in rare species and with medicinal properties. This type of feeding directly influences the quality of the products obtained, especially the taste and aroma.

As shown in the specialized literature, the organoleptic characteristics of animal products are directly influenced by the quality and floristic composition of the pastures. The aroma of milk is influenced by volatile substances from the plants that make up the flora of natural meadows, such as dandelion, yarrow, pennyroyal, wild carrot, plantain or mint. The pleasant taste of milk is given by its sugar content, and the texture is determined by the proportion of fats. In other words, the diversity and richness of the vegetation of the meadows is directly reflected in the quality of the milk. In contrast, milk obtained from animals grazing on grasslands composed exclusively of grasses (such as golomăț, ryegrass or fescue) has a weaker, less specific aroma. This characteristic is associated with the presence of hexane in these plants, which favors the oxidation processes of the milk. Furthermore, when the grasslands contain a high proportion of toxic species, the milk acquires an unpleasant, repulsive aroma, often described as "plastic", "metallic" or "pharmaceutical" notes, due to odoriferous compounds specific to these plants (Dragomir, 2017).

Traditional pastoralism remains an essential practice in mountain areas, being carried out mainly by small farmers or shepherds who take their flocks to high-altitude pastures. This way of life involves an outdoor activity that supports a natural growth of the animals and actively contributes to the maintenance and conservation of the mountain landscape.

Mountain food products are obtained through traditional processing methods, passed down from generation to generation. Burduf cheese, mountain cheese, telemeau or urda are produced by hand, from fresh milk, often raw or minimally processed, and are naturally matured. These products have an intense and distinct taste, thanks to the mountain pastures and traditional production methods. Similarly, mountain meat and meat preparations, such as sausages or ham, are smoked or dried without the use of chemical additives or industrial preservatives, preserving an authentic and natural taste.

Another distinctive element of mountain food is the use of local natural resources. Mountain herbs used in animal feed, but also medicinal or aromatic plants used in the preparation of food or drinks, give the products a unique aromatic and gustatory profile, appreciated for its authenticity.

Seasonality also plays an important role in mountain production. Many products, such as cheeses or dried meat, are only produced during certain periods of the year, especially when the pastures are at their most nutrient-rich. Thus, agricultural and livestock activities in mountain areas are closely linked to the natural cycles of vegetation and the weather conditions specific to the altitude (Tregear, Arfini, Belletti & Marescotti, 2007).

Tourism contributes significantly to the development of mountain production, as in many regions there is an increased demand for traditional products from tourists interested in authentic tastes and local culture. As a result, mountain products are not only intended for local consumption, but also reach foreign markets, where they are appreciated for their naturalness and superior quality.

From an ecological point of view, production activities in mountain areas are generally more sustainable. Farmers in these regions use environmentally friendly working methods, avoiding the use of chemicals or industrial fertilizers. These practices contribute to the conservation of biodiversity and the maintenance of a balanced mountain ecosystem. At the same time, the relatively low production volume specific to these areas implies a lower consumption of industrial energy, which makes mountain products more "eco-friendly".

Last but not least, mountain regions are distinguished by a special biodiversity, and food production is constantly adapting to local conditions. Medicinal plants or berries that grow only in certain areas give uniqueness to the products obtained here. This natural diversity, combined with traditional production methods, makes mountain foods offer not only a high level of quality, but also a valuable cultural and ecological experience, in harmony with the environment and local traditions.

1.3. The role of mountain products in the economy

Mountain food products play an important role in the economy of mountain areas. These products are characterized, as already mentioned, by a superior quality, due to the specific natural conditions in which they are produced, as well as the traditions and processing methods that are based on old, authentic techniques. Mountain food products are appreciated for their special taste that is due to the natural growing conditions of plants and animals: alpine meadows, clean air, unpolluted soils. These give the products quality and authenticity.

Many of the mountain food products benefit from certifications (mountain product or organic product certification), giving them an important advantage on domestic and international markets. These certifications guarantee that the products are obtained in a sustainable way, without the use of pesticides or chemical fertilizers, making them attractive to consumers concerned about health and the environment. They are produced according to old recipes and techniques, preserving the connection with the local culture, adding an added value due to their unique and rare character.

Mountain food products, by their specificity, have led to the development of gastronomic tourism, restaurants and guesthouses that serve traditional local menus. The organization of fairs with traditional gastronomic specificity attracts tourists who, in addition to the amounts spent on purchasing these products, spend additionally on accommodation, transport or other local products, not necessarily food.

In Romania, food festivals are a great way to celebrate local culinary traditions, promote authentic products and attract tourists from all over the world: the National Cheese Festival (Brădet, Argeș County), the “Tastes and Traditions” Festival (Brașov), the Sarmale Festival (Iași), the “Pensiunii si Gustului Montan” Festival (Moieciu de Sus, Brașov), the “Culture and Tastes” Festival (Sibiu), the “Deliciilor din Pădure” Festival (Vama, Suceava), the “Sărbătoarea Pensiunilor” Festival (Maramureș County). These food festivals in Romania are a great way to experience the country’s culinary diversity and support local producers, while also being an opportunity to get to know the traditions and customs of each region better. Mountain food products can be exported, in the context of the growing demand for authentic and organic products (Gruyère from Switzerland, Feta from Greece, Ibănești from Romania), attracting a wide audience due to the stories behind them, the traditional production methods and the superior quality, especially in Europe where the emphasis is on organic and traditional products.

Mountain agriculture is an important source of income for rural communities. Raising animals (for milk, meat or cheese), cultivating mountain plants (berries, medicinal plants), beekeeping are economic activities that support the livelihood of local people. Mountain food products resulting from these activities contribute directly to the diversification of the regional economy, providing jobs in the livestock and beekeeping sectors, but also in downstream sectors such as retail and tourism. Mountain agriculture is less intensive than agriculture in plains, hills and hills, being more attentive to the conservation of biodiversity and the natural landscape. This sustainable approach contributes to protecting the environment. Mountain food production is linked to the management of natural resources, such as forests and mountain pastures, which contributes to maintaining a beneficial ecological balance for the entire region.

We can appreciate that mountain food products are a symbol of mountain regions and are essential for supporting local economies and for the development of rural and ecological tourism. Due to their added value, diversity and health benefits, these products represent an important source of income and can contribute significantly to sustainable economic growth in mountain areas.

3. Quality labelling: concept and applicability

3.1. Conditions for use of the quality term "mountain product"

The "mountain product" label can be applied to a wide range of food or non-food products originating from mountain areas and complying with strict criteria of origin, processing and quality. In the case of products of animal origin, this label is valid if the animals are raised and the products are processed in mountain areas. More specifically, the products may come from animals that have lived entirely in these regions or at least for the last two thirds of their lives, provided that the processing also takes place in the mountain area.

Products obtained from animals raised in transhumance can also be certified, if they have grazed on mountain pastures for at least a quarter of their lives. As regards animal feed, the label applies when the proportion of feed originating from outside mountain areas does not exceed 50% of the annual ration, expressed as a percentage of dry matter.

In the case of ruminants, this limit is even stricter, at 40%, and for pigs it must not exceed 75%. For beekeeping products, certification is only possible if the bees have collected pollen and nectar exclusively from mountain areas. In the case of products of plant origin, the essential condition is that the plants are entirely cultivated in these regions. Also, products containing ingredients originating from outside mountain areas can be certified as "mountain products" only if these ingredients do not exceed 50% of the total weight of the product. This exception applies, for example, to aromatic plants, spices or sugar used in processing.

There are also situations in which certain processing operations may take place outside the mountain area, provided that the distance does not exceed 30 kilometres. This concerns the slaughtering of animals, cutting and boning of carcasses, in the case of products obtained from animals raised for at least the last two thirds of their lives in mountain areas. The certification of mountain products aims to guarantee consumers that the products come from regions where the environment is less affected by pollution and where agricultural practices are in harmony with nature. These products comply with strict standards of quality, sustainability and tradition.

In the European Union, the certification system for mountain products recognises several important aspects, including organic certification, which certifies that production methods exclude the use of pesticides and harmful chemicals. Another defining element is the link with local traditions, the products being made using techniques passed down from generation to generation. Geographical origin also plays a key role, as these products are closely linked to the natural characteristics of the mountain region they come from. The "mountain product" label thus offers not only a guarantee of quality and authenticity, but also recognition of the cultural and ecological value of products from these areas.

3.2. Benefits and limitations of mountain product certification

Certification of mountain products brings a number of significant benefits, both for producers and for local communities, consumers and the environment. Through this process, the superior quality, authenticity and sustainability of products from mountain areas are recognized, contributing to a balanced and sustainable development of these regions. One of the main advantages of certification is the facilitated access to premium markets, both domestic and international.

Certified mountain products are perceived as being of high quality, which makes them attractive to consumers looking for natural, traditional and organic foods. This allows producers to better value their products, obtain higher prices and even expand into foreign markets, where the demand for authentic and sustainable products is growing.

Certification also contributes to the promotion and protection of local traditions. Production methods passed down from generation to generation are preserved and valorized, giving the products a strong cultural identity. In this way, the continuity of traditional crafts is ensured, which otherwise risk being lost to modern industrial processes.

Another major benefit is the stimulation of sustainable economic development in mountain areas. Through certification, small producers are supported in maintaining and diversifying their activities, contributing to the creation of new jobs and the economic revitalization of mountain communities. At the same time, certified products attract the interest of tourists, which supports the development of rural and mountain tourism.

Environmental protection is another essential aspect of certification. Certified mountain production involves nature-friendly methods, based on ecological and sustainable principles. Thus, biodiversity is protected, soil and water quality are maintained, and mountain ecosystems are preserved in the long term. These practices contribute to combating land degradation and reducing negative environmental impacts.

For consumers, certification offers clear guarantees of quality, safety and traceability. The "mountain product" label becomes an indicator of trust, signaling that the product comes from a clean environment, was obtained by traditional methods and has a reduced impact on the environment. This transparency increases the level of trust and loyalty towards mountain products.

In addition, certification can attract funds and institutional support for the development of mountain regions. By officially recognizing mountain products, authorities can more effectively support support policies for these areas, contributing to reducing territorial disparities and protecting natural and cultural heritage.

Last but not least, certification helps to preserve local identity, promoting traditions, customs and lifestyles specific to mountain regions. This provides official recognition of the cultural value of these products, strengthening the sense of belonging and local pride. Overall, certification of mountain products becomes an essential tool for supporting a development model that values nature, people and mountain traditions.

3.3. Advantages of mountain food products

The advantages of mountain food products are multiple and are reflected both in the benefits for the health of consumers and in the positive impact on the environment and local communities. These products are often obtained from clean and ecological natural resources, which reduces the risk of the presence of chemicals or additives, thus contributing to the promotion of consumer health.

The certification of mountain food products stimulates local consumption, encouraging a diet based on regional, healthy and authentic products. At the same time, this helps to reduce the carbon footprint, due to the shortening of supply routes, which has a beneficial effect on the environment.

Another essential benefit is rigorous quality control, as certification involves periodic checks that guarantee compliance with strict food safety and quality standards throughout the production process. Thus, consumers can trust that certified mountain products comply with the criteria of authenticity and safety.

In addition, certification contributes to the sustainable use of mountain resources, helping to manage them responsibly and preventing excessive or irresponsible exploitation, which supports the long-term conservation of the natural environment.

Another important aspect is the increase in transparency and trust in the supply chain. Certified mountain food products are accompanied by a clear traceability system, allowing them to be followed from the production phase to processing and marketing.

Certification thus becomes a guarantor of transparency and compliance with the criteria imposed by the “certified mountain product” label. In addition, certified mountain food products are often promoted through educational campaigns aimed at raising consumer awareness of the importance of choosing healthy, organic and high-quality foods.

In the case of products of animal origin, certification can also include animal welfare standards, ensuring that they are raised in natural and humane conditions, without stress or abusive treatment, which gives added value to the products and an additional guarantee for consumers.

Thus, certified mountain food products represent a beneficial choice not only for consumer health and satisfaction, but also for environmental protection, support for local traditions and the sustainable development of mountain areas.

4. The mountain product certification process

The mountain food product certification procedure is a rigorous process, regulated both at national and European level. It aims to guarantee that the products come from authentic mountain areas and that they comply with the specific standards imposed for this category. Among the mandatory requirements are the provenance of raw materials from mountain regions, the use of traditional processing technologies and the respect of clear limits on transport and processing.

Mountain products must reflect the special environmental, climatic and biodiversity conditions of the area. Certification ensures full traceability of the product, from producer to consumer. In addition, the “mountain product” label offers a competitive advantage in the market, increasing the confidence of buyers. This labeling contributes to the sustainable development of mountain areas and the support of small local farmers. The process involves periodic checks and controls carried out by the competent authorities. Ultimately, certification not only guarantees quality, but also protects the identity and regional specificity of mountain products.

Figure 1 – Mountain product logo

4.1. Stages of mountain product certification

The certification of mountain food products begins with the submission of a certification application. The producer submits to the competent authority or authorized body an application that includes, in addition to its identification data and the geographical area of origin, detailed information about the product, the production process and its methods of exploitation.

The next step consists of verifying the product’s compliance with the regulations in force. The certification authority or body analyzes whether the product meets the criteria necessary to be considered a “mountain product”.

The third stage involves the preparation of a certification file that includes essential information such as the origin of the raw materials, the processing methods, the geographical characteristics of the production area, the quality standards respected, as well as documents attesting compliance with food safety requirements.

Subsequently, the inspection or on-site checks take place. Inspectors authorized by the certification body carry out checks on farms, processing units and other places where the product is obtained or processed, check the composition and quality of the product in the laboratory and evaluate its traceability, to ensure transparency and authenticity.

If the product meets all the criteria, the certification authority or body issues the “mountain product” certificate, which includes details about the product, the production method, the geographical area of origin and the quality standards respected. The product is labeled based on the certificate obtained and must contain the certification number, the specific logo and mentions of compliance with ecological standards, if applicable.

After obtaining the certificate, the process does not end, but continues with permanent monitoring and control to ensure continued compliance with the standards. In the event that non-conformities are identified, producers may be sanctioned depending on the severity of the deviations, and their certification may even be withdrawn. Upon expiration of the period for which the certificate was issued, it is necessary to renew it in order to maintain its validity. The renewal process involves going through the same procedure as in the case of the initial issuance, which implies fulfilling all the specific requirements and checks established by the issuing authority. Thus, the certificate retains its validity and compliance with the rules in force, ensuring the continuity of the rights or functionality it confers.

4.2. Regulations on the certification of mountain food products

Depending on the country of origin of the mountain food product, there are specific regulations that certify its authenticity and provenance. The certification process can involve both international or European standards and national regulations. In Romania, as well as in other European countries, there are various certifications and labels that guarantee the quality and mountain origin of food products.

An example of this is the Protected Designation of Origin (PDO) or Protected Geographical Indication (PGI) label, which confirms that a product comes from a specific region and that all stages of the production process take place exclusively in that area. Also, the ISO 22000 standard, which focuses on food safety management, is relevant for mountain products, especially those intended for export or international markets, guaranteeing that the products are safe for consumption.

Mountain food products obtained through organic methods can benefit from organic certification, either through national or European certifications, such as Biocert or the EU organic certification. These certifications attest to compliance with organic standards, which involve the avoidance of pesticides, chemical fertilizers and other practices harmful to the environment.In addition to these, there are also additional international certifications such as GlobalGAP, Fair Trade or UTZ, which are particularly relevant for mountain food products sold on foreign markets. Thus, certified mountain food products must comply with both external standards, such as PDO, IGP, Eco-Label or organic certifications, and internal regulations imposed by national and regional authorities. (Regulamentul CE nr.834/2007, Regulamentul CE nr. 889/2008).

These requirements ensure that the products are of high quality, safe for consumption and come from mountain areas that respect local traditions, environmental protection and sustainability principles. In order to obtain and maintain certification, farmers and producers must be transparent and comply with all legal regulations in force.

5. Quality indicators and monitoring tools

The quality indicators of certified mountain food products represent a complex set of characteristics that describe and ensure their high quality, authenticity and safety. These indicators are fundamental to guaranteeing that mountain products comply with the requirements imposed by the certification authorities and meet consumer expectations. They include both objective, measurable elements and subjective aspects related to sensory perception, reflecting the physical qualities of the product, but also the production methods.

An essential aspect is the clearly defined geographical origin, so that a certified mountain food product must come from a mountain area according to national or European regulations, where the landforms exceed 600 meters in altitude. Products can benefit from geographical certifications such as Protected Designation of Origin (PDO) or Protected Geographical Indication (PGI), which attest that the product was created, processed and prepared in that region, using traditional local techniques. Certified mountain products respect traditional production techniques, methods passed down from generation to generation, essential for preserving authenticity and local identity. In addition, they follow traditional recipes specific to the mountain area, which may involve the use of local ingredients and particular preparation methods.

The quality of the ingredients is another important indicator, as these products are made from raw materials from mountain regions, where climatic conditions and soil favor the cultivation of high-quality aromatic plants, vegetables, fruits or dairy products. Often, production is carried out using ecological or sustainable methods, such as organic farming or extensive animal husbandry, without the use of chemicals and artificial fertilizers, which gives the products a natural and healthy character.

In terms of food safety and quality, certified mountain products are subject to strict regulations, including rigorous laboratory tests that confirm the absence of contaminants or their presence within acceptable limits, such as heavy metals, pesticides or harmful microorganisms. The certification process involves regular audits and inspections, which verify compliance with quality standards and the implementation of traceability systems to track the product throughout its entire journey, from farm to consumer.

Respect for the natural environment is another essential aspect. Certified mountain products are closely linked to the protection of the mountain environment, and their production must comply with requirements aimed at preserving the landscape, biodiversity and ecological balance of the area. Thus, they are produced sustainably, with minimal impact on ecosystems and support local economic development in an environmentally responsible way.

The taste quality is another strong point of these products. They are recognized for their authentic taste, which reflects the specifics of the mountain region, and artisanal products, made in small quantities, offer a superior taste experience and characteristic aromas, due to both natural ingredients and traditional processing techniques.

Certified mountain products bring important health benefits, being generally less processed than industrial products and having a higher content of essential nutrients, such as vitamins and minerals. The natural conditions in which animals are raised and plants are cultivated contribute to this superior nutritional value.

Finally, authenticity and limited production are other defining characteristics of certified mountain food products. They are manufactured in limited quantities and, most often, only available during certain periods of the year, which gives them an exclusive character and makes them highly appreciated by consumers looking for unique and high-quality products.

6. National Register of Mountain Products

The National Register of Mountain Products is a register of the Ministry of Agriculture and Rural Development (MADR) that includes specific, traditional and authentic products from the mountainous areas of Romania. The purpose of this register is to protect, promote and valorize products made in the mountain environment, ensuring compliance with clear criteria regarding their origin, production methods and authenticity.

This register provides producers with official recognition and support in promoting their products, and provides consumers with the certainty that they are purchasing authentic products, while supporting the local economy in mountainous areas. To be included in the register, products must meet strict standards related to provenance, quality and tradition, thus also benefiting from special protection against imitators or counterfeiters.

The frequency of updating the National Register of Mountain Products may vary depending on the regulations of the Ministry of Agriculture and Rural Development (MADR) and specific administrative procedures. In general, such registers are updated periodically, at least once a month, to reflect new entries, changes or deletions of the products and units included.

Thus, on August 31, 2025, 4,527 products were registered in the National Register of Mountain Products, of which 543 (12%) were in the milk and dairy products category

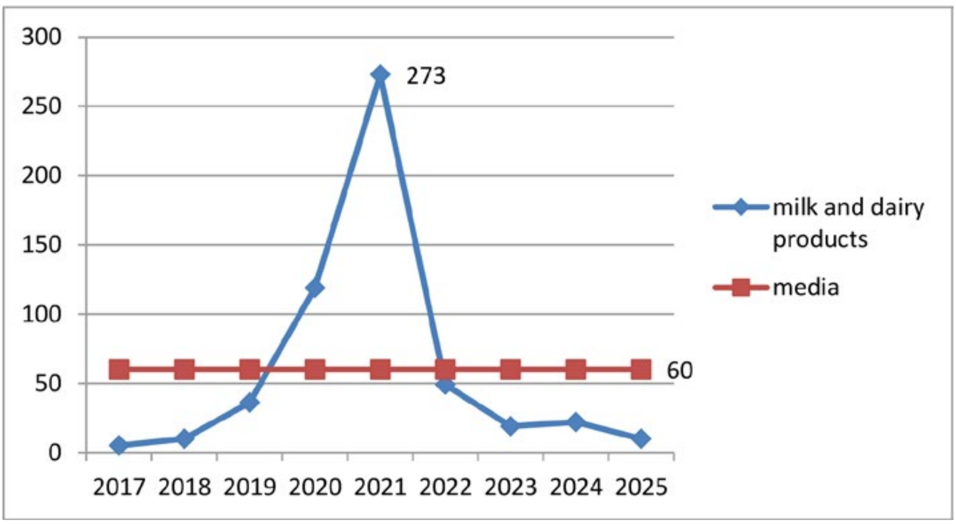

Figure 1 - Dynamics of registration of milk and dairy products in the National Register of Mountain Products
Source: own calculations according to NRMP, July 30, 2025

The image shows the evolution of the number of products in the milk and dairy products category registered in the National Register of Mountain Products between 2017 and 2025, compared to a constant reference average (60 units annually). During the analyzed period, their number recorded a fluctuating evolution. Between 2017 and 2021, a significant increase was noted, from 5 products in 2017 to a maximum of 273 products in 2021, a value considerably above the reference average of 60 units. After this peak, a sharp decrease occurred in 2022, falling to 49, followed by a decreasing trend in the following years.

Although the period 2019–2021 shows an increased interest in registering mountain dairy products, the decreasing trend in the following years highlights either a decrease in production capacity or problems in the certification and maintenance process in the register. Compared to the average, only 2 years (2020 and 2021) performed significantly, the rest falling well below expectations. This could signal the need for interventions to support, inform or simplify procedures for mountain producers (Figure 1).

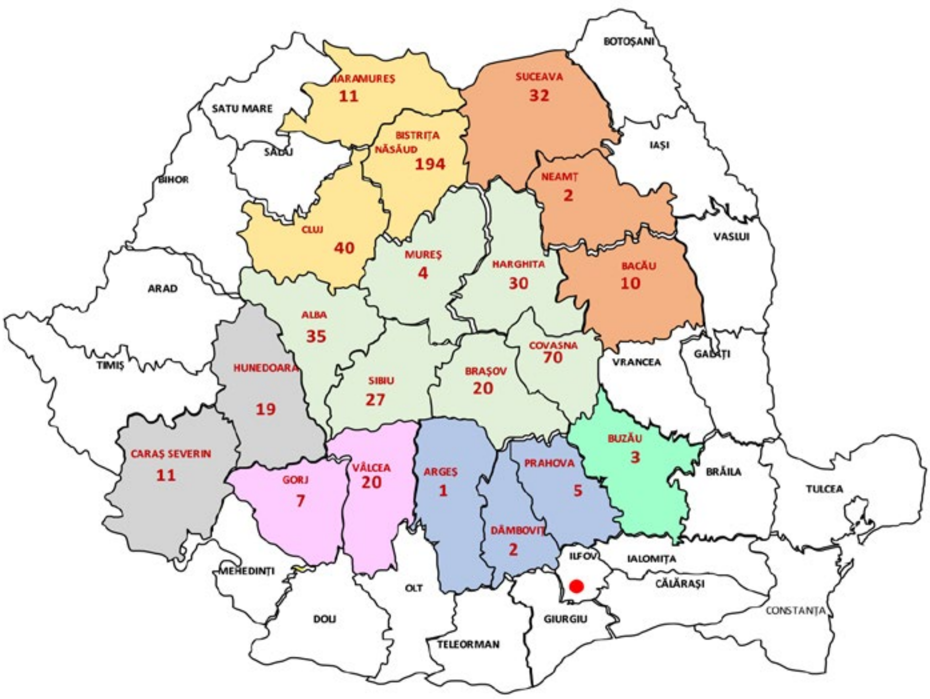

Figure 2 - Geographical representation of milk and dairy product producers
Source: own calculations according to NRMP, July 30, 2025

The analysis of the distribution of certified mountain products in the milk and dairy products category, reported to the counties and development regions of Romania, highlights significant differences in the degree of exploitation of the mountain potential.

The highest concentration is found in the North-West Region, with a total of 245 certified products, of which 194 belong to Bistrița-Năsăud County, which is a detached leader at national level. Cluj contributes with 40 products, and Maramureș with 11. This region demonstrates sustained activity in the certification process of mountain dairy products, reflecting a good mobilization of local producers and, most likely, the existence of efficient administrative support.

In second place is the Center Region, with 186 certified products, in counties such as Covasna (70), Alba (35), Harghita (30), Sibiu (SB27) and Brașov (20). This performance is consistent with the mountainous agri-food tradition of the area and the local infrastructure that supports the promotion of traditional products. In contrast, in the North-East, South-West Oltenia and South-Muntenia regions, the number of certified dairy products is low, with 12, 7 and 8 products registered in the register, respectively.

Although these regions have counties with mountainous terrain and a tradition in animal husbandry, the low number of certifications indicates an undervaluation of local resources, possibly caused by a lack of information, bureaucracy or difficulties in accessing the certification process. For example, in the counties of Neamț, Gorj, Argeș or Dâmbovița, only a few certified mountain products are registered, although the production potential exists.

This uneven distribution of certified mountain products highlights the need for more balanced public policies, an awareness campaign at local level, as well as a simplification of certification procedures. More intensive promotion of this quality system could contribute to increasing the number of certified products and, implicitly, to the sustainable development of mountain areas.

Conclusions

In conclusion, although the certification of mountain products brings important benefits in terms of product valorization, environmental protection and promotion of local traditions, the limitations and challenges from the perspective of farmers remain real and significant. In order for more producers to be motivated to join this system, it is essential that the authorities simplify the procedures, provide concrete and accessible support and create clear conditions for the superior valorization of these products on the market.

Romania's efforts have resulted in a fairly high degree of adoption of the term in a short period of time, especially compared to other countries. However, the "mountain product" quality scheme has not yet demonstrated its full potential for most producers, although some perceive and report benefits associated with it, such as slight profit increases and greater customer loyalty.

The "mountain product" quality scheme could be a useful public policy instrument to increase the income of mountain product producers and protect mountain agriculture in Romania, as it can fill a gap in an otherwise binary market of "organic" or "non-organic" products.

Moving to the level of public strategies and policies offers several options for implementing the "mountain product" certification system and organizing the related market.

Considerable benefits can be obtained by adopting a participatory governance model, based on cooperation between public and private actors. In support of this approach, some concrete examples are also provided regarding the application of these principles in the specific context of "mountain product" certification.

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THE INFLUENCE OF DIFFERENT TILLAGE SYSTEMS ON THE MORPHOLOGICAL, PRODUCTIVE CHARACTERISTIC AND GRAIN YIELD OF TWO WINTER WHEAT VARIETES

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Abstract. The study on the influence of reduced cultivation technology on the morphological and productive traits of winter wheat was conducted at the ,,Radmilovac" experimental field, managed by Faculty of Agriculture, University of Belgrade. The field trial was set up and carried out during the 2022/23 season, as twofactorial, with three replications, on soil type classified as chernosem luvic. The size of each elementary plot was 6 m2. The first factor (A) was the tillage system, with three following variants: Convetional tillage (CT) that represents plow ploughing to a depth of 25cm, as well as pre-sowing cultivation with disc harrow and harrow; Mulch tillage (MT) performed by chisel plow, to a depth of 25cm without inverting the soil, leaving over 30% of crop residues on the soil surface; The third tillage system is based on manual direct sowing, without preliminary tillage, leaving all crop residues on the soil surface. The second investigated factor (B) involved two selected winter wheat cultivars (NS Zvezdana & NS Rajna), grown in a four crop rotation with maize as preceding crop. In all plots, basic fertilization in autumn was performed using NPK (15:15:15) fertilizer at a rate of 600 kg ha-1. Additional nitrogen fertilization was applied in the form of ammonium nitrate (AN) at a rational rate of 60 kg/ha N. Sowing was carried out on October 7th 2022 and harvesting took place in early July 2023. On average, the greatest stem lenght was recorded in the no-tillage system (94,09 cm) while the lowest was observed in the mulch tillage system (82.36 cm), which represents a statistically highly significant difference. The longest average spike length occurred in the mulch tillage system (8.85 cm), whereas the shortest was in the conventional tillage system (7.96 cm), however, the difference between these values was not statistically significant. In terms of grain weight per plant, the highest average value was recorded in the no-tillage system (11.9 g), although this did not differ significantly from the lowest average value found in the conventional system (10.1 g). The highest average grain yield was also observed in the no-tillage system (5.42 t ha−1), which was not statistically significantly different compared to the lowest yield in the conventional tillage system (4.54 t ha−1). The application of rational nutrient inputs and conservation tillage systems can result in satisfactory yields and favorable morphological characteristics, thereby supporting the principles of sustainability, preserving key resources, and enhancing the production of winter wheat.

Keywords: cultivar, fertilization, tillage systems, sustainability

1. Introduction

Agriculture represents the foundation for food production, serving both human and animal populations. With the continuous growth of the global population, the demand for food has also increased, leading to the intensive exploitation of key natural resources. However, careless and improper use of these resources results in their depletion and degradation. Crop production today relies heavily on various mechanized operations, as well as the application of irrational quantities of fertilizers and plant protection products, which ultimately disrupt both economic and ecological stability.

To reduce the risks associated with these issues, new and improved agricultural technologies have been developed, alongside reductions in existing systems that call for modifications to current cultural practices. These modifications aim to align with the principles of sustainability by limiting the intensive use and consumption of resources and reducing environmental pollution.

Since the earliest days of agricultural production, humans have recognized that appropriate soil tillage systems can improve certain soil properties, enhance fertility, and provide favorable conditions for plant growth. This, in turn, enables high and stable yields while protecting the soil from weeds, insects, and various pathogens, and maintaining its productive capacity. Consequently, soil tillage is considered the oldest agrotechnical measure. Diverse experiences in soil management have led to the development of numerous technical systems that are applied based on various factors [1].

Tillage must be adapted to the local climate, soil type, topography, fertilization practices, production system, erosion risk, crop variety, previously cultivated crops, and other site-specific conditions [2]. A well-chosen tillage system is a crucial factor which, when combined with proper crop rotation and fertilization, ensures high efficiency and the rational use of soil fertility.

As one of the key agrotechnical practices, soil tillage is intended to create optimal conditions for the growth and development of cultivated plants. It is therefore essential to prepare the land for cultivation and to utilize its productive capacity regularly throughout each growing season. The reduction of conventional tillage systems has been driven by the need to simplify cultivation processes and by the development of new tools and technologies aimed at lowering production inputs, ultimately reducing the cost of the main agricultural product. Moreover, reducing the number of tillage operations does not negatively impact productivity, while increasing overall efficiency and producing several positive outcomes. These include improved soil structure, preservation and enhancement of fertility, and reduced labor, costs, and time required for individual operations. However, some drawbacks still exist, mostly related to the application of organic and mineral fertilizers, as well as weed, pest, and disease control [3].

In addition to proper tillage, meeting the nutritional needs of crops is essential. To preserve and enhance the soil's capacity to support high yields and favorable morphological traits, it is necessary to regularly or periodically replenish nutrients lost through harvest, leaching, and other processes. This must be done in a way that does not harm the soil or negatively affect the cultivated plants [4].

Considering the importance of winter wheat in agricultural production and human nutrition, and the fact that its cultivation requires the application of various agrotechnical practices, the objective of this study is to determine the effects of reduced tillage technologies on the morphological and productive traits and grain yield of two winter wheat cultivars.

2. Material and Methods

This research was conducted at the ,,Radmilovac" experimental field, managed by the Faculty of Agriculture, University of Belgrade. The field trial was established and carried out during 2022/23 growing season as twofactorial with three replications, on a chernosem luvic soil type. The selected wheat cultivars were grown within a four crop rotation system, with maize as preceding crop, The surface of each elementary plot was 6 m2.

For the purpose of this study, three soil tillage systems were applied, representing factor A of the experiment:

1. Conventional Tillage (CT): this included plow ploughing to a depth of 25cm, as well as pre-sowing cultivation with disc harrow and harrow;
2. Mulch Tillage (MT): Soil was tilled using chisel plow, to a depth of 25cm without soil inversion, leaving over 30% of crop residues on the soil surface, followed by discing and harrowing;
3. No Tillage system (NT): Which is based on manual direct sowing, without preliminary tillage, leaving all crop residues on the soil surface.

Primary tillage operations were carried out in early October, followed immediately by pre-seeding cultivation.

Basal fertilization was conducted simultaneously using NPK fertilizer (15:15:15) at a rate of 600 kg ha-1. On March 10th 2023. all treatments were top-dressed with nitrogen in the form of ammonium nitrate (AN) at rational rate of 60 kg ha-1 N

For the cultivation of winter wheat, two carefully selected winter wheat cultivars were selected (NS Zvezdana & NS Rajna), representing factor B of this experiment. NS Zvezdana responds well to elevated nitrogen levels and exhibits good lodging resistance, whereas NS Rajna requires higher input levels and more intensive agrotehnical measures. Under optimal growing conditions, both cultivars are capable of achieving yields exceeding 9 t/ha.

Weed control was carried out with Maton in tillering if stem elongations were 1.0 l ha−1 (in the CT plot) or 0.5 l ha−1 (in the MT and NT plots). Unify in an amount of 0.8 l ha−1, and Ison in an amount of 0.6 l ha-1, were used to protect plants against fungal diseases.

Sowing was performed on October 7th 2022, the sowing density of wheat was 550 seeds per m2. Harvesting took place in early July 2023, when wheat samples were also collected.

The collected data on morphological and yield related traits were statistically analysed using analysis of variance (ANOVA), while individual treatment comparisons were conducted using the LSD test.

2.1 Meteorological conditions during experiment

Meteorological conditions at the experimental site are presented graphically in Figure 1. The climatediagram is constructed using data provided by the Republic Hydrometeorological Servise of Serbia (RHMZ) for the Belgrade area, covering the period from October 2022 to June 2023.

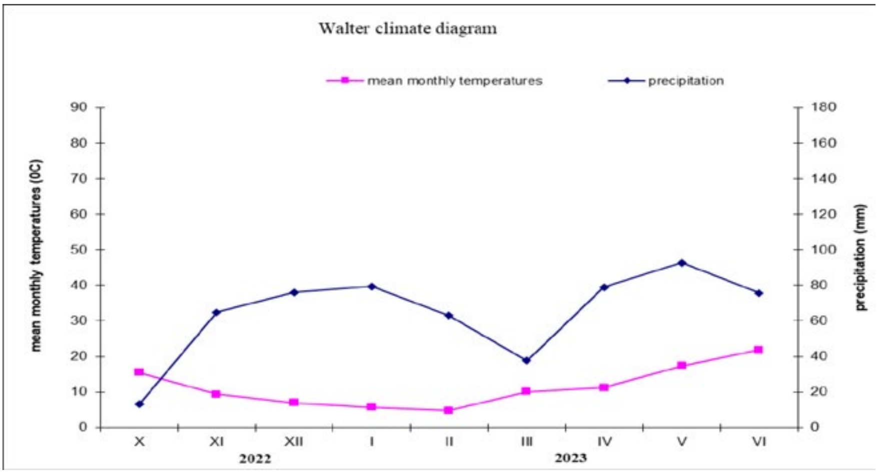

Figure 1: Climatediagram for the Belgrade Area (October 2022 – June 2023)

The average monthly temperature during investigated period was approximately 11^{0}C, while the total precipitation amounted to about 581 mm over the vegetation period. From the climate diagram presented in Figure 1, a dry period can be observed in October, characterized by high temperature and low precipitation. This period coincided with the timing of primary tillage, pre-sowing preparation and sowing. Adequate soil moisture during this phase is essential for proper seed germination and early plant development. However, such condition were lacking in October, leading to delayed emergence and poor root establishment of wheat, despite the fact that more favorable weather conditions occured in November.

In the subsequent months, temperatures remained within the optimal range for wheat development, altough some extremes were recorded, such as unusually warm and relatively wet December. These atypical conditions may have negatively influenced certain morphological traits of the plant. The lack of rainfall in March coincided with a critical period of intensive wheat growth, which adversely affected the final grain yield, resulted in lower than expected productivity.

3. Results and disscussion

Data on the impact of different soil tillage systems on the morphological and productive traits of the selected wheat cultivars are presented in Table 1.

Table 1. Effect of different tillage systems on morphological and productive traits of selected wheat cultivars

Stem lenght (cm)			
Tillage systems (A)	Winter wheat cultivars (B)		Average A
	NS Zvezdana	NS Rajna	
	Average AB		
CT	80.87	85.18	83.03
MT	79.39	85.33	82.36
NT	99.37	88.81	94.09
Average B	86.54	86.44	
Spike lenght (cm)			
CT	7.44	8.49	7.96
MT	8.91	8.79	8.85
NT	7.7	8.87	8.28
Average B	8.02	8.72	
Grain mass per plant (g)			
CT	5.87	14.33	10.01
MT	6.53	16.46	11.49
NT	11.1	12.7	11.9
Average B	7.83	14.49	

Table 2. Thresholds of significance depending on the examined factor

Stem lenght		
LSD	0.05	0.01
A	4.648	6.375
B	3.795	5.205
AB	6.574	9.016
Spike lenght		
A	1.011	1.386
B	0.825	1.312
AB	1.429	1.961

Grain mass per plant		
A	3.093	4.242
B	2.525	3.463
AB	4.374	5.998

The thresholds of significance depending on the examined factor are representented in Table 2.

On average, the greatest stem length is recorded under the no tillage system (94.09cm), while the shortest stems are observed under the mulch tillage system (82.36 cm), which represents a statistically highly significant difference. When considering the average stem length by cultivar, no statistically significant differences are found. However, cultivar NS Zvezdana exhibit the longest stem under no tillage system (99.37 cm), which is significantly longer compared to NS Rajna under thr same system (88.81 cm) representing a highly significant difference. The shortest stem is observed in NS Zvezdana under the mulch tillage system (79.39 cm), but the comparison with the shortest stem of NS Rajna (85.18 cm) did not reveal a statistically significant difference.

Regarding spike length, the highest average value is recorded under the mulch tillage system (8.85 cm), while the lowest average spike length is found under the conventional tillage system (7.96 cm), however, this difference isn`t statistically significant. The longest spike is recorded in NS Zvezdana under the mulch tillage system (8.91 cm), closely followed by NS Rajna under the no-tillage system (8.87 cm), The difference between these values is not statistically significant. The shortest spike is found in NS Zvezdana under the conventional tillage system (7.44 cm). For NS Rajna, the shortest spike also occurr under the same tillage system, with a length of 8.49 cm, again, the difference between these values is not statistically significant.

If we compare the data on spike length with findings of [5] it can be concluded that the spike length of the NS Dragana variety, which measured 9.22 cm under conventional tillage, is greater than the average spike length of the varieties examined in this study, which was 7.96 cm. However, the spike length of NS Dragana in the no tillage system was 7.60 cm, which is shorter than the spike lengths of the cultivars investigated in this study (8.28 cm). Based on the obtained data, it can be stated that soil tillage, soil type, different meteorological conditions, and variety selection all have an influence on spike length.

Regarding grain mass per plant, the highest average value is observed under the no tillage system (11.9 g), altough there is not statistically significant difference when it comes to the lowest average value, recorded under conventional tillage system (10.1 g). On average, NS Rajna produced a higher grain mass per plant (14.49 g), which is statistically highly significant when compered to NS Zvezdana, which has an average grain mass of 7.83g per plant. The lowest grain mas is recorded in NS Zvezdana under the convencional tillage system (5.87 g), while the highest was observed in NS Rajna under the mulch tillage system (16.46 g), this difference is statistically highly significant.

Data about grain yield of selected wheat cultivars is represented in Table 3, while you can find the thresholds of significance for this examined factor in Table 4.

Table 3. Effect of Different Tillage Systems on the Grain Yield of Selected Wheat Cultivars

Cultivars			
Tillage systems (A)	Wheat cultivars (B)		Average A
	NS Zvezdana	NS Rajna	
	Average AB		
CT	3.23	5.79	4.54
MT	3.59	6.69	5.14
NT	6.11	4.73	5.42
Average B	4.31	5.74	

Table 4. The thresholds of significance for grain yield

LSD	0.05	0.01
A	1.615	2.215
B	1.318	2.284
AB	1.808	3.132

On average, the highest grain yield is recorded under the no tillage system (5.42 t ha−1), although this value is not statistically significantly different from the lowest yield observed under the conventional tillage system (4.54 t ha−1). The cultivar NS Rajna produced a significantly higher average yield (5.74 t ha−1) compared to NS Zvezdana (4.13 t ha−1), which represents a statistically significant difference.

The highest yield is achieved by NS Rajna under the mulch tillage system (6.69 t ha−1), and this was statistically significantly higher than the yield of NS Zvezdana under the same tillage system (3.59 t ha−1). The lowest yield is recorded for NS Zvezdana under the conventional tillage system (3.23 t ha−1), which is statistically highly significantly lower when compared to the highest yield of NS Rajna, and also statistically significantly lower when compared to the highest yield of NS Zvezdana, achieved under the no tillage system (6.11 t ha−1).

According to [6], who investigated the influence of year and location on winter wheat yield, the highest yields were obtained at the Pančevo site in 2017 (9.64 t ha−1), while the lowest yields were recorded in the same year at the Požarevac location (5.92 t ha−1). Compared to the cultivars tested in this study, the yields reported by [6] were significantly higher, which can be attributed to different meteorological conditions, locations, and cultivar selection.

According to [7], the average yield of certain wheat cultivars under conventional tillage in a trial conducted during the 2003/04 – 2004/05 seasons was 3.51 t ha−1, while the yield with top-dressing of 60 kg ha-1 N was 2.93 t ha−1 .These yields are significantly lower than those obtained in the present study, where the average yield was 4,54 t ha−1. A similar trend was observed for the mulch tillage system, where [7] reported average yields of 2.75 t ha−1and 2.48 t ha−1with 60 kg ha-1 N top-dressing, respectively. For the no-tillage system, average yields were 2.32 t ha−1without and 2.01 t ha−1 with nitrogen top-dressing. In contrast, the current study recorded yields of 5.14 t ha−1 under mulch tillage and 5.42 t ha−1 under no-tillage. These differences in yield can be attributed to innovations in tillage practices as well as more favorable weather conditions during the experimental period, given that the trials were conducted in different years. Furthermore, conventional tillage systems require more intensive inputs and tend to produce higher yields than conservation tillage systems when higher fertilizer rates are applied. However, this advantage is only temporary. Over the long term, the drawbacks of conventional tillage become apparent, particularly its detrimental effects on soil health [8].

According to [9], the grain yield of winter wheat was highly influenced by tillage system tehnology. The grain yield of winter wheat was higher in CT plots than at MT and NT plots. The highest grain yield was in in the CT system with a high N dose (5.91 t ha−1), and the lowest was in the NT system with a reduced N dose (4.65 t ha−1). We have different case in the current experiment. When it comes to NS Zvezdana, the highest grain yield is represented in no-tillage system (6,11 t ha−1t/ha), while the lowest yield is in CT system (3.23 t ha−1). NS Rajna cultivar reached the highest grain yield in the MT system (6.69 t ha−1) and the lowest one is in NT system (4.73 t ha−1).

4. Conclusion

Based on the results of this study, it can be concluded that both soil tillage systems and wheat cultivars must be chosen rationally and carefully to achieve the desired outcomes. Lower yields and poorer morphological traits were obtained under the conventional tillage system, which may be attributed to the long-term use of this method. All examined morphological and productive traits showed higher values under no-tillage and mulch tillage systems, which was the main objective of the study. Therefore, it is necessary to adapt production technology to innovative approaches and reduced tillage systems.

The key to success lies in adhering to the principles of sustainable agriculture and selecting cultivars that can achieve desired yields and traits without requiring special soil management conditions or excessive fertilizer inputs. This was demonstrated in the current study, as nitrogen top-dressing was applied at a rational dose, yet significant yields and positive characteristics were achieved.

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IOT IN INDOOR PLANTING

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Abstract. Nowadays, it is impossible to imagine a world without automation. A frequently used system that enables automation processes is the Internet of Things (IoT). The IoT is a system that brings together multiple technologies and techniques to create a connected network of devices. IoT devices find their way into homes through smart watches, air conditioners, cars, etc. The application in agriculture is also significant. Indoor cultivation of microgreens is often a side business, and growers don't have the whole day to monitor the microgreens. The question that arises is how to improve and smartly manage the cultivation of microgreens. According to that, the main goal of this project is to use the IoT for tracking parameters that are important, and sending them to the web for analysis and further control. In order to do that, microcontroller boards such as Raspberry Pi and Arduino Nano as well as the sensors DHT 11 and a capacitive soil moisture sensor are employed. The Raspberry Pi is used as the main brain of the project, while the Arduino Nano is used for listening and executing orders. The DHT 11 sensor is used to measure air temperature and humidity, and a capacitive soil moisture sensor is used for soil moisture. LED lights and a step motor are controlled through a web interface and can be accessed from anywhere. The Raspberry Pi V2 camera is placed on the edge of the rotating axis, and determines the stages of the microgreens by means of a Machine Learning (ML) model. In this way, two modes can always be used, automatic and manual, so that the growers can customize their own growing experience. This physical network of devices is especially useful for those people who want to grow their food but don't have enough time to keep an eye on everything, so it is easier for them if someone gives them exact data on what they need to do and when. This is exactly what this smart IoT project offers. It is necessary to connect the IoT project to the internet and track the desired data. In addition, a trained ML model helps to decide which stage a microgreen is in and what to do next.

Keywords: Indoor planting, IoT, Raspberry Pi, Arduino Nano and sensors

1. INTRODUCTION

Microgreens have become increasingly popular in recent years. People grow them in their basements, and small to mid-sized companies grow them on indoor farms. Whatever the growing method, there are challenges in actively measuring their status. The commonly used method for monitoring the growth of microgreens involves the use of: visual inspection, sensors and Internet of Things (IoT).

The first method is most commonly used because it doesn't require investment in expensive equipment. However, if you rely only on your eyes, you may notice problems too late, since you can't watch your microgreens all day. Low-cost sensors help, but they mostly provide surface-level information. Using the Internet of Things is best because it provides real-time, accurate information on microgreen status and can actively change that status, making an independent system that doesn't rely on human presence. This paper emphasizes using the fast-developing field of artificial intelligence, machine learning and deep learning, to improve the monitoring of microgreens. By implementing these technologies, you can track microgreens by color, determine their current growth stage, and identify what they need most to grow well.

The goal of this paper is to implement a deep learning model to analyze the stage of microgreens. In this way, we can track their growth stage and provide what they need in a timely and appropriate manner.

2. MATERIAL AND METHODS

In our work, for the experimental setup, we use:

- Raspberry Pi 4 Model B (8 GB RAM) as a master;
- Arduino Nano (ATmega328P) - as a slave;
- Raspberry Pi Camera Module v2 (Sony IMX219, 8 MP) for image acquisition;
- DHT11 digital sensor (data acquisition to Arduino);
- Aideepen capacitive soil-moisture sensor (analog output);
- 5 V LED grow strip (for plant illumination); and
- 3D-printed electronics enclosure (project-specific).

Figure 1. Overview of experimental IoT system.

The Raspberry Pi acts as the master and represents the main core of IoT projects, while the Arduino Nano acts as the slave. In automation terms, the master performs high-level decision-making, while the slave reports measurements and executes commands. In experimental setup, the camera and the Arduino are connected to the Raspberry Pi (USB serial). The Arduino handles all low-level I/O: two sensors (air temperature/humidity and soil moisture), LED strip and stepper motor. The LED strip and the stepper motor are powered by an external power supply, with a common ground, to prevent unintended resets caused by voltage drops. The process works in two phases: ZERO and INTERVENTION.

ZERO phase is the term for the first cycle that the shaft makes. In this phase, it goes one full circle while taking images, and then returns, still taking images. In total, it takes 24 images (12 on the forward pass and 12 on the return). Each captured image is analysed using a MobileNetV2 model [1]. When the entire cycle is completed, deap learning model counts how many images belong to each growth stage and determine the current stage of the microgreens based on the percentage. Based on this decision, we proceed to the Intervention phase. The Intervention phase is divided into three stages: GR - Germination, GP - Growth and PH - Pre-harvest.

In the germination stage, the microgreens are still dark/black and at this stage, they require a dark environment with slightly higher temperature and humidity. The temperature should be between 22-25°C, while the humidity reaching from 65-80 % of relative humidity. Accorcing to the capacitive sensor, the soil moisture should be between 250-400 of its raw reading. When the Deep Learning model decides that the microgreens are in this stage, we turn off the LED light and indicate in the app that the plants are in the Germination stage, which means that they need darkness and a slightly higher temperature and humidity.

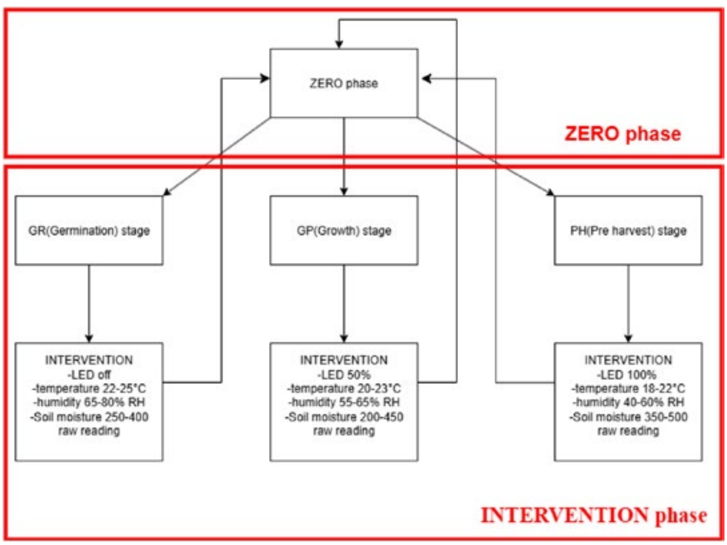

Figure 2. Workflow Diagram.

During the growth stage, the microgreens require 55-65% relative humidity and a temperature of 20-23°C. At this stage, the stepper motor slowly rotates one full cycle of the shaft and then returns shaft to its original position, while the LED light is set to 50% of maximum power (PWM 128). Raw values of the capacitive sensor should be 200-450.

In the pre-harvest stage (PH), the microgreens are green and fully developed, and before harvest it is neceserly wait a few more days. For this reason, the LED is set to full power, which means PWM is 255. The temperature should be 18–22°C and the relative humidity 40-60%. Raw values of the capacitive sensor should be 350–500.

Each stage lasts exactly 10 minutes, after which the model automatically returns to the ZERO phase and restarts the decision-making process. In this way, we reduce time in each stage and increase the precision of the system.

3. RESULTS AND DISCUSSION

3.1 Deep Learning Model

In our work, we used a convolutional neural network, MobileNetV2 pre-trained with the ImageNet dataset. We fine-tuned this model for our three microgreen stages. This transfer-learning setup uses features learned from ~1.2 million images (edges, textures, shapes), and was further tuned to our stages, enabling efficient training with a small dataset [1,2]. We labelled 300 images and split them into training and validation folders. Each of these folders has 3 subfolders with images of our stages. In the training folder, there are 3 subfolders labelled as our stages and each has 80 images, while the training folder has 20 images per stage. We trained a model to decide which stage our microgreen is in, and the resulting classifier achieves an accuracy of 73% on the held-out test set.

```
Overall accuracy: 73.33%

Confusion matrix (rows=true, cols=pred):
             GP      GR      PH
      GP     18       0       2
      GR      0      20       0
      PH     14       0       6
```

Figure 3. Accuracy of model.

After fine-tuning, the model was exported to TensorFlow Lite, a lightweight version of TensorFlow optimized to run on devices with lower memory and processing power.

3.2 Accuracy of the Deep Learning Model

The achieved accuracy of 73% is to be expected given the small amount of fine-tuning. Even though the model was pretrained with the large ImageNet dataset, it still needs more images per stage to better distinguish between the stages. However, even without adding more images to our dataset, there are other ways to increase the accuracy: data augmentation (brightness/contrast, small rotations, blurring [3]) and training refinements (cosine learning-rate decay, label smoothing [4]).

3.3 Discussion

Deep learning in this work is the perception module within a broader IoT system. Running on the Raspberry Pi, the model classifies the plant's growth stage from images, and the IoT controller uses that decision to adjust light, moisture, and temperature-closing the loop from sensing to actuation. It is expected that deep learning-based decision support in IoT systems will become increasingly widespread in the coming years.

4. CONCLUSIONS

In this work, the beginning of implementing Sony IMX219 camera in small indoor microgreens production is presented. A camera is used to capture images of microgreens, which are then processed by a convolutional neural network MobileNetV2. This is all part of the IoT system we are developing that can make the determination of the stage the microgreens are in. For future work, we will analyse two directions of development:

1. A scientific approach to building a better and more accurate system; and
2. A commercial approach.

For a scientific approach we would try a few things:

- Increasing the accuracy of our model with techniques discussed earlier;
- Switching from an RGB to a multispectral camera;
- Trying different types of processors to increase efficiency;
- Developing an algorithm that will make decisions based on multiple input parameters acquired from different sensors; and
- Adding actuators that react after deciding what the problem is.

All these approaches need more time and knowledge, as well as a bigger team that will work on them. For a commercial approach, it is necessary to analyse the market for this type of device, and, based on that, correct the device presented in this paper.

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