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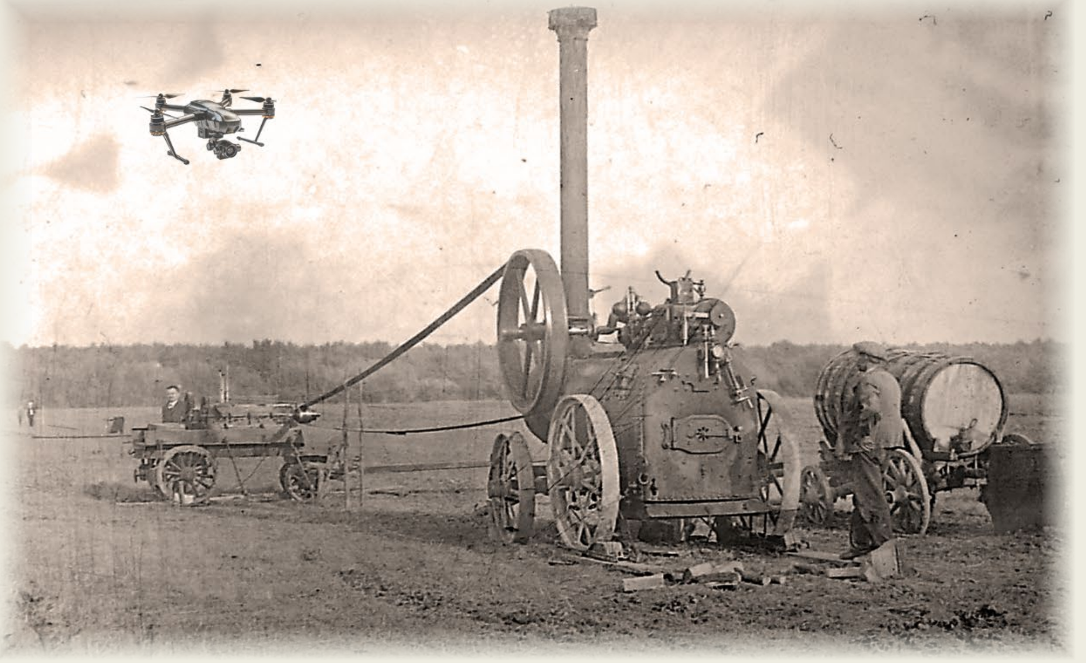
PROCEEDINGS OF THE 50th INTERNATIONAL SYMPOSIUM

ACTUAL TASKS ON AGRICULTURAL ENGINEERING

OPATIJA, CROATIA, MARCH 11th - 13th 2025



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CONTENTS

50. ACTUAL TASKS ON AGRICULTURAL ENGINEERING

Preliminary communication

EXPERIMENTAL METHODOLOGY ON AGRICULTURAL TRACTOR EMISSIONS AND CONSUMPTION ANALYSIS BY MEANS OF LABORATORY TESTS

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ABSTRACT

The exhaust gases generated by tractors do not only pollute the air but also damage agricultural products in the vicinity. They are also carried to agricultural lands by wind or rainfall, causing negative effects on soil and water resources. This situation reduces the quality and yield of agricultural products, leading to both economic losses and negative consequences on food safety. Taking into account all these factors, this study includes a test campaign conducted on a classic narrow-track vineyard tractor. The aim of the study is to characterize the performance, consumption and pollutant emissions produced by the engine. Considering the engine's operating capacity and emission gas production capacity, different test points were designed. Various operating points of the engine were tested at different rates at partial load and the data were then subjected to statistical analysis. The results are presented through Brake Specific Fuel Consumption (BSFC) and (Brake Specific Emission Level) BSEL maps. Such mapping provides useful information for the evaluation of pollutants emitted as engine operating parameters change.

Keywords: *Tractors, pollution, consumption, dynamometer, BSFC*

INTRODUCTION

AFOLU (Agriculture, Forestry, and Other Land Use) sector is responsible for the 18% of gas emission (United Nations Environment Programme, 2024), largely due to the implements of tractors as mobile power plants in various agricultural activities.. Farm tractors are used as mobile power plants in agricultural production and have an indispensable importance in a wide range of agricultural activities such as planting, irrigation, fertilization and harvesting. Almost all agricultural machines and equipment have to be operated by the traction power, the mechanical power (as torque on the PTO output shaft) and/or by means of hydraulic systems, all three available on of these powerful vehicles. However, the high-power output of tractor engines comes with it a significant amount of diesel fuel consumption, which causes a high rate of spread of unsatisfactory emission gases in the atmosphere (Bacenetti et al., 2018) (Han et al., 2021) as carbon monoxide (CO), nitrogen oxides (NO_X) particle matters (PM) and hydrocarbons (HC). Considering the increasing environmental awareness and sustainability goals through the world in recent years, minimizing the effects of this pollution, especially in agricultural areas, has become extremely considerable. In the last decades both European Union and corresponding US Environmental Protection Agency have been introduced regulations as 2016/1628(EU) to limit the pollution levels forcing the manufacturers to introduce emission control systems also in No Road Mobile Machinery (NRMM). It is also important to define strategies to analyse the engine emissions' level under a certain load and engine speed. Since mapping all the possible working condition of the tractor engine creating proper BSFC and BSEL is time and money consuming, many studies has been carried out in real conditions exploiting the data continuously coming from electronic control unit recording engine revolutions and fuel injection quantity with the aim methodology to understands how real life factors influence pollution emission (Janulevičius et al., 2017) or using Portable Emissions Measurement Systems (PEMS) installed directly on the tractor (Merkisz et al., 2017)(Kim et al., 2024). Some study trying to analyse the amount of exhaust emission trying to replicate real field condition performing indoor test (Ettl et al., 2022) (Galli et al., 2024).

This study wants to describe the methodology applied evaluating the consumption and level of emission measured during an experimental campaign performed indoor by the AFILab of the Free University of Bolzano located in the NOI Techpark on a narrow-track vineyard tractor. The aim of the work is to create BSFC and BSEL maps to be used for future evaluation. Since the fleet of this type of tractor in Italy has an average age of over 20 years (Bietresato et al., 2015), it was decided not to use a newly manufactured tractor.

MATERIALS AND METHODS

The tractor used for this test was a New Holland TN75V registered in 1999 and with more than 5000 workings hours to date whose specification are reported in Table 1.

The tractor engine test bench consists in a Sigma 50 PTO Dynamometer manufactured by Froment Ltd (Stamford, UK) to measure torque power and rotational speed, a scale Kern DS 30K0.1L to measure the fuel consumption, a gas analyser MRU MGA PrimeQ, an Opacimeter MRU Optrans 1600 for the exhausts, a datalogger Datataker DT85M Series 3 used just for thermocouples and an exhaust vacuum system. The gas analyser probe is provided with a thermocouple. The gas analyser is a EN 15267-4 certified one and equipped with a paramagnetic sensor for measuring O_2 and with 8 Non-Dispersive Infrared Sensors (NDIR) for measuring pollutions as CO, CO_2, NO, NO_2 and HC as CH_4 C_3H_8.The tractor is equipped with an ISO 500 PTO Type 1 having a nominal speed of 540 rpm.

Table 1. Datasheet of the tractor New Holland TN75V used for the test (CNH Industrial, 1999)

Engine	Turbo Diesel
Engine Type	IVECO 8035.25.529
Number of cylinders	3
Engine displacement	2931 cm^3
Maximum Power	53 kW @ 2300 rpm
Maximum Torque	293 Nm @ 1400 rpm
PTO/Engine rpm ratio	565/2300
Unladen Mass	2355 kg
PTO	Type 1 540 rpm

The engine is connected to the Dynamometer by the tractor PTO. Thermocouples are connected to the fuel lines, engine thermostat, oil pan and exhaust manifold. All instruments are equipped with serial communication ports so that they can be connected directly to the data acquisition laptop. Opacimeter and gas analyser probes are inserted in an exhaust manifold located downstream of the tractor exhaust. To avoid modifying the tractor's original fuel line, it was decided to use an auxiliary tank resting on the scale and connected to the tractor's original tank via a fuel hose and a modified tank cap (Figure 1). The strategy for measuring consumption involves filling the tractor's original tank completely and measuring the change in the amount of diesel fuel in the auxiliary tank over time. All the data recorded from the equipment are sampled at 1 Hz by a Laptop Dell Latitude 5424 Rugged i7 with 32GB of RAM equipped with a NI LabView interface specially developed for this test (Figure 2) (Bietresato et al., 2019).

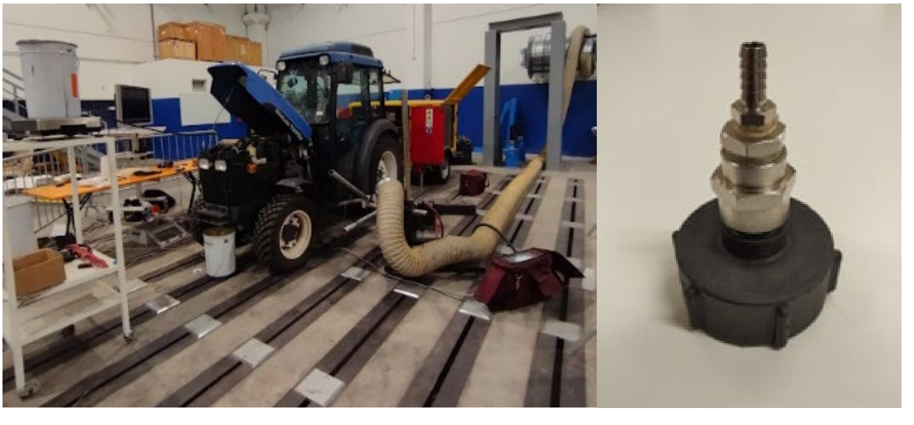

Figure 1. Engine Tractor test bench and modified tractor tank cap

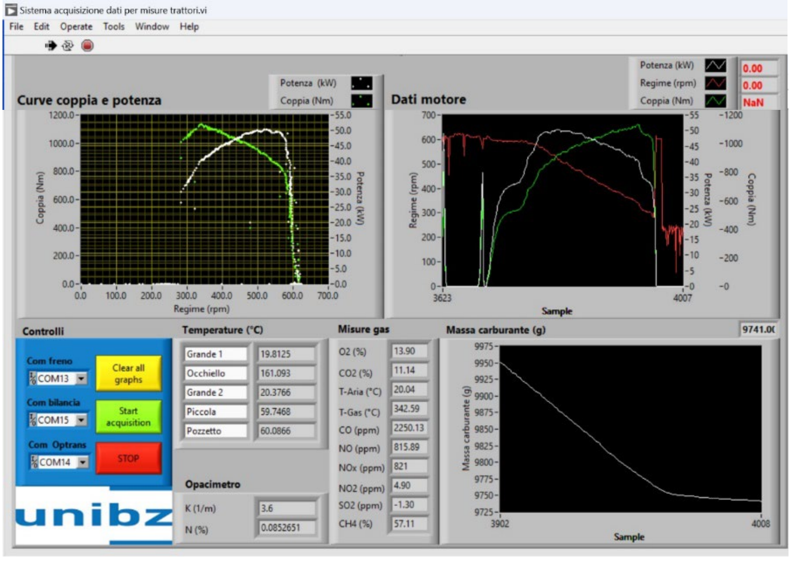

Figure 2. NI LabView interface for the tractor engine acquisition data

Tests were carried out at both maximum and partial load. To have a reliable value of the accelerator pedal position during partial loads tests and to avoid altering the factory settings of the injection pump, an additional adjuster has been inserted on the injection pump to limit the stroke of the governor lever (Figure 3). In this way, the operator only had to hold down the accelerator pedal at any partial load. The Dynamometer applies loads on the tractors' PTO to prevent its rotational movements. The control logic of the dynamometer allows different types of tests: automatic, constant speed, constant power, and direct.

Figure 3. Additional adjuster on the fuel injection pump

At idle speed, the PTO is engaged, and the throttle is moved to the desired position. When the automatic mode is selected, the dynamometer will start braking the engine progressively, automatically obtaining the torque and power curves. In constat speed mode, the logic control brakes the engine to keep the selected rotational speed constant. In constant power the logic control keeps the selected power value constant. Before carrying out the tests at constant rotation speed, the tractor engine was correctly started and brought to operating temperature. After some preliminary tests on the statistical significance of the data collected, it was agreed that to have statistically acceptable values, especially for pollutant emissions, each individual test should have a duration of at least 150 seconds. For the pollutions' evaluation it was decided to consider just the last 40 seconds of each test, 150 seconds for the consumptions' evaluation.

A total of 46 different steady-state operating points were chosen to describe the engine's entire operating map, and among these were all the points specified by the OECD's Code 2(OECD, 2024) for official tractor engine testing.

Post data processing was performed under Spyder environment with a code developed in Python 3.13 by the authors.

In the absence of an air flow meter during the test run, the operating value from the air/fuel mass ratio was derived from the values measured with the exhaust gas analyser using the combustion reaction balance equations (Ferrari, 2008; Heywood, 1988).

The overall combustion reaction can be written as:

$$C_nH_mO_r + \frac{n_{O_2}}{\phi}(O_2 + 3.773N_2) =$$
$$n_P\left(\tilde{x}_{C_aH_b}C_aH_b + \tilde{x}_{CO}CO + \tilde{x}_{CO_2}CO_2 + \tilde{x}_{O_2}O_2 + \tilde{x}_{N_2}N_2 + \tilde{x}_{NO}NO + \tilde{x}_{NO_2}NO_2 + \tilde{x}_{H_2O}H_2O + \tilde{x}_{H_2}H_2\right) \quad (1)$$

Where ϕ is the fuel/air equivalence ratio, $\tilde{x}_i$ is the mole fraction the i-species and n_{O_2} is the number of O_2 molecules required to complete the combustion.

$$n_{O_2} = n + \frac{m}{4} - \frac{r}{2} \quad (2)$$

The equation (1) has seven unknowns: $\phi, \tilde{x}_{H_2}, \tilde{x}_{H_2O}, \tilde{x}_{N_2}N_2, n_P, a, b$. All the other values are obtained from the gas analyser. To solve for the seven unknows, considering that for unburned HC it is possible to assume that *b/n=m/n*, it is necessary introduce additional equations to balance the mole number of carbon, hydrogen, oxygen, nitrogen and adding up all the molar fraction to 1.

The balance equation of the dissociation of CO_2 and H_2 into CO and H_2O can be described by the following equation:

$$\frac{\tilde{x}_{CO}\tilde{x}_{H_2O}}{\tilde{x}_{CO_2}\tilde{x}_{H_2}} = K \quad (3)$$

Where K is 3.5 (EU Commission, 2017).

For this study the value of unburned hydrocarbons $\tilde{x}_{C_aH_b}$ are neglected and diesel fuel has been assimilated to $C_{16}H_{34}$.

RESULTS AND DISCUSSION

Tractor performance data are showed in Figure 4 and summarized in Table 2.

Table 2. tractor performance data from experimental data

Maximum power	56.02 kW @ 2550 rpm
Maximum torque	244 Nm @ 1800 rpm
Rated engine speed	2730 rpm
Rated torque	188 Nm
Rated power	53.88 kW
Constant power range	533 rpm
Torque rise	29.80 %
Engine speed drop	34.09 %

Engine's performance values slightly differ from those declared by the manufacturer. Maximum power has a higher value and maximum torque a lower value both of them reached at a higher engine speed.

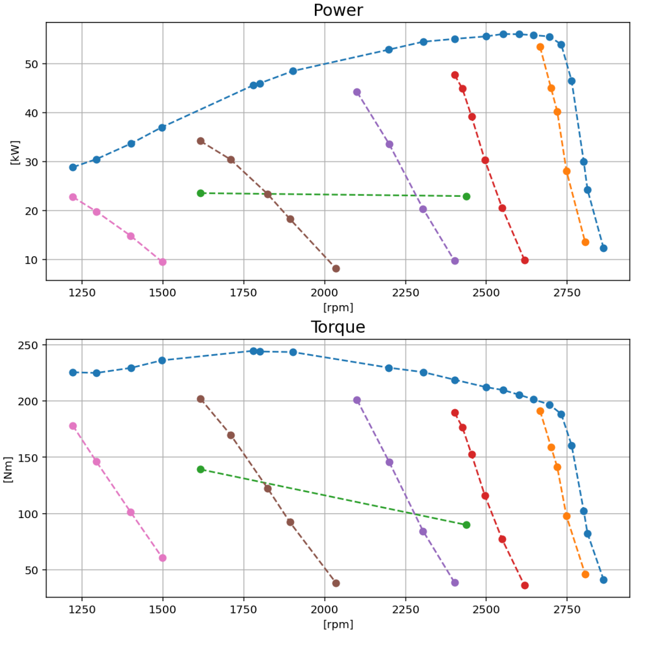

Figure 4. Engine Power and Engine Torque varying Engine Speed

In Figure 5 engine efficiency is reported. At full load with the rotational speed between the max torque value and the max power value the engine presents an efficiency of more than 35%. This value is also reached at low load. Considering that the tractor is equipped with a direct injection engine fed by a conventional mechanic rotary pump and a turbocharger without intercooler, it demonstrates the good health of the engine.

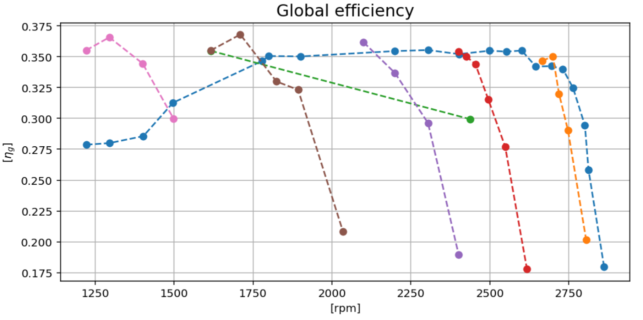

Figure 5. Global engine efficiency varying the engine rpm

Figure 6 shows the engine maps for brake specific fuel consumption and emissions. Values are expressed in *g/kWh*. These maps explain for each engine operating point the level of fuel consumption and specific emissions and are obtained by interpolating the various experimental data. A grid of 800 x 800 points has been set to create the maps.

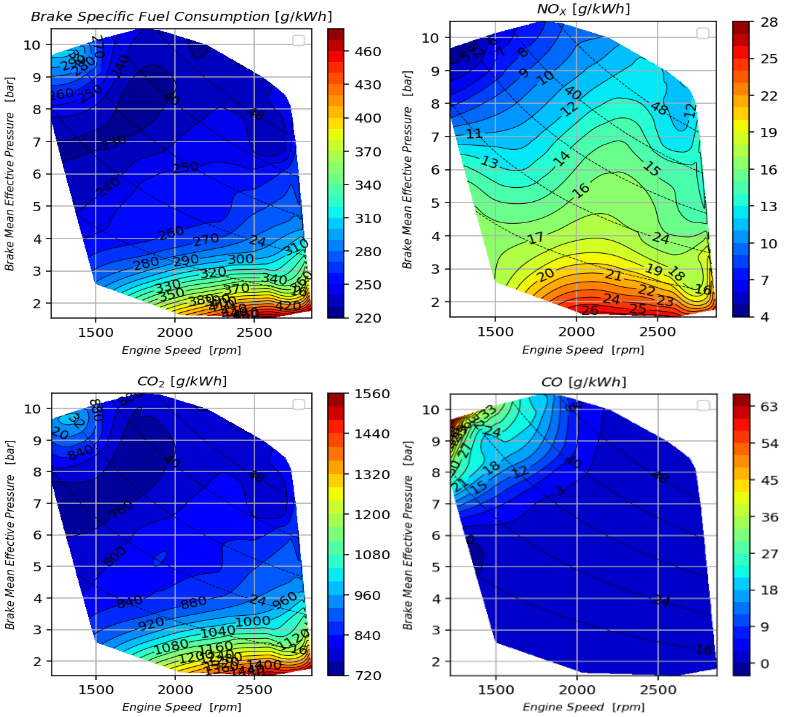

Figure 6. Brake Specific Fuel Consumption, NO_x, CO_2, and CO maps [g/kWh]

The upper border of the map represents the shape of the torque curve at maximum load. The lowest specific consumption for this engine has a value of approximately 226 g/kWh and it is not achieved at maximum load but at partial load as also showed by the corresponding high efficiency values in Fig. 5. The efficiency in this point reach 36.8% The specific CO_2 graph obviously has a similar trend to the specific fuel consumption graph. The highest specific CO value is 66 g/kWh, and it is reached under high load and low RPM conditions, i.e. with very high resistant torque or high tractor drag such as a steep climb or high transported load. At higher speed the amount is reduced to less than 3g/kWh. The highest specific NO_X value is 26 g/kWh, and it is reached in those conditions where the engine has very low loads while they have a minimum value of 5 g/kWh at low-speed engine and high load.

CONCLUSIONS

Exhaust gases generated by internal combustion engines have a direct impact on environmental pollution. In an agricultural context that makes use of agricultural tractors with an average age of 20 years, it is necessary to understand their level of emissions released in the atmosphere.

This study presented an experimental methodology used to map the specific fuel consumption and pollutant emissions of an agricultural tractor engine registered in 1999 by means of tests in a laboratory. The tested tractor, even tough is not recent, still present a high fuel conversion efficiency. The engine performance slightly differs from the data released from the tractor builder. These maps can be used to develop strategies with the aim to optimize the engine performance during the various agricultural activities and to evaluate numerically the emissions released into the environment during field activities.

ACKNOWLEDGEMENTS

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ROLLOVER STABILITY IN TRACTORS: A MULTIBODY DYNAMICS AND EXPERIMENTAL PERSPECTIVE

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ABSTRACT

Tractors generally work on uneven and sloped fields, which leads to safety problems. Rollovers are caused by these conditions and account for more than half of all tractor accidents. In Italy, from 2002 to 2012, 43.7% of fatal accidents related to mechanization involved tractors, with 57.4% of them resulting from rollovers. Even if they are not fatal, financial losses due to both damage to equipment and interruption of activity are inevitable. The study of this topic through simulation and experimental activities is therefore very important. It is plausible to characterize the stability in every operative condition and develop more adequate active and/or passive safety systems. In this study, a vineyard tractor has been tested. Two different methods were used: 1. Multibody dynamics (MBD) simulations and 2. Rollover tests performed using tilt table. First, an MBD model was created with the software Adams/View. Then a test-rig was exploited to measure the position of the centre-of-gravity (CoG). A series of rollover test were then carried out considering different CoG configurations and orientations with respect to the line of maximum slope on MBD environment. As a result, various stability maps are obtained for comparison. This is a graphic tool that represents the behaviour of the machine in each configuration with regards to stability. Results showed that the stability behaviour of the machine has no linear relationship with the CoG shift in lateral and vertical direction.

Keywords: *Tractor Rollover Stability, Agricultural Vehicles, Multi Body Dynamics, Stability Test, Tilting Platform*

INTRODUCTION

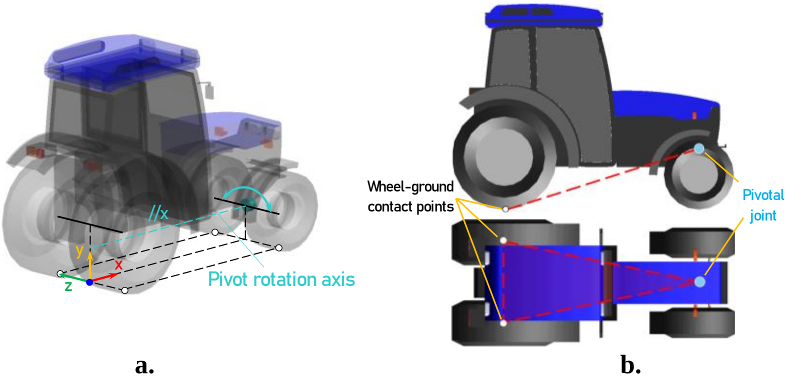
Tractors have been evolving since the beginning of agricultural mechanization. Since they currently serve as a power source for different agricultural machines in addition to their primary functions such as pulling and carrying, they have become an indispensable part of agricultural mechanization. Although tractors consist of four wheels and a body like a vehicle, they show some differences from traditional vehicles due to their features. One notable difference lies in their safety concerns, as tractors often operate in challenging environments such as slippery or soft surfaces, narrow pathways, and sloping terrain. These harsh conditions increase the possibility of vertical level differences between the wheels is higher compared to vehicles operating on flat roads (Wong, 2001). Such differences may prevent all wheels from sustaining contact with the ground and increase the risk of tractor rollover.

Most accidents in the agricultural sector still occur during tractor use, and more than half of tractor-related deaths are known to be caused by rollover accidents. A study revealed that the average of 1310 fatal accidents per year occurred worldwide in the past decade due to tractor rollovers (Togaev and Shermukhamedov, 2023). Considering the difficult terrain conditions where tractors operate, it is stated that the main causes of rollover accidents are sloping terrain and sudden, sharp turns (Felaco et al., 2023). Improper use of protective equipment such as seat belts and ROPS also increases the risk of fatal accidents (Micheletti Cremasco et al., 2020). A study on accidents in agricultural fields in Turkey revealed that almost 35% of all accidents are caused by tractor rollovers (Alçayır and Hacıseferoğulları, 2017). Considering the variety of possible accidents, this rate is quite high and reveals the need to increase precautions against tractor rollover accidents. Jang et al. (2024) found that rollover accidents are the most influential reasons of these accidents are unbalanced centre-of-gravity (CoG), poor ground conditions and high speeds. Therefore, it is vital to examine the stability behaviour of tractors depending on the change in the CoG position. Majdan et al. (2021) explored the effect of a rear ballast weight on tractor lateral stability by comparing the experimental data with the theoretical standards. They proved that a rear ballast improves the lateral stability of a tractor as the ballast level is lower than the CoG position of the tractor which results in the decrease of the overall CoG level. Koo (2022) highlighted the effect of the rear implements on rearward rollover of a tractor while optimizing the efficiency of the rotary-base rear implements. Jang et al. (2022) utilized Multibody dynamics (MBD) simulations to understand the lateral and backward rollover behaviour of a tractor with a multifunctional front implement. They specifically examined the effect of different obstacles with various shape and height, and different road inclination angles. Results showed that the backward rollover is most likely to happen when the ground slope is lower while lateral rollover occurs with the higher inclination. Bietresato and Mazzetto (2022) introduced the possibility of testing implemented machines by using a specific test-rig designed for the evaluation of the rollover performance of agricultural vehicles. Franceschetti et al. (2021) developed a kinematic model for the lateral stability of an articulated narrow-track tractor and validated the accuracy of the model with lateral stability tests. The study showed that not only the roll angle but also the yaw angle between two solid bodies of an articulated tractor influences the lateral stability angle. Zhou et al. (2023) composed an MBD model of a half-track tractor to investigate the dynamic performance of the vehicle on soft and hard surfaces and validate the accuracy of the model with experimental and theoretical data. They evaluate the vehicle in terms of straight-line driving offset, average speed, front wheel steering and articulated steering.

In the scope of this study, the applicability of MBD analysis as a computer-aided method for the evaluation of the rollover stability of tractors in case of an implement attachment was examined. The main purpose was to investigate the influence of the CoG position change of the tractor stability and propose a tool to estimate the potential risk of some certain implementations. Firstly, the CoG position of a vineyard tractor was determined by a stability test-rig according to ISO standards. Afterwards, a realistic MBD model was composed, and different implements were mounted to the tractor to understand the possible range of the CoG position shift in every direction of the tractor. To investigate the effect of these changes on stability, the range between the maximum and minimum values was divided into equal intervals with specific step sizes, and analyses were conducted on the values within this range. The results were visualized using stability maps. Realistic mechanical features, such as the front pivot axle geometry and degrees-of-freedom (DoFs) of the platform, were simulated in the MBD analyses, which were validated through experimental test results. In addition to the rollover test methods defined in ISO standards (only pure lateral), this study evaluated the tractor stability behaviour across all orientation angles. The obtained results provide important data in terms of understanding the effects of changes in the CoG position on stability and encouraging the use of alternative evaluation methods in tractor design.

MATERIALS AND METHODS

In traditional tractors, pivotal front axle construction is employed in order all four wheels to remain in contact with the ground regardless of the conformation of the land. When one of the wheels encounters a bump or pothole and falls to a different plane from the others, the connection of the four wheels to the ground continues without interruption up to a certain limit due to the mechanical behaviour of this specific structure. The axle construction consists of a rigid axle, two bumpstops positioned symmetrically along the lateral axis on the axle that determine the mechanical rotation limit of the body, and a revolute joint located at the centre of the axle. The rigid axle and the body can rotate relative to each other around the longitudinal axis of the vehicle until one of the bumpstops is activated (Previati et al., 2014). This value is ±5° for the tractor discussed in this publication. The schematic representation of the front axle geometry can be seen in Figure 1.a.



a. **b.**

Figure 1. **a.** Scheme of the front axle and the axis system of the tractor and **b.** Stability region for Phase 1 instability

This construction leads to a different evaluation of tractor stability than traditional vehicles. While the axle and the body retain rotational DoF relative to one another, the stability zone is determined not by the contact point of the front wheels but by the kinematic rotation centre of the pivot joint. In other words, there is a mechanical and fixed instant rotation centre determined for stability. Consequently, the stability zone is not a rectangle formed by the ground contact points of the four wheels, but a triangle formed by the pivot centre of the front axle and the ground contact point of the rear wheels, and the overturning moment occurs around the axes of this triangle. This instability phase of the tractor is referred to as Phase 1 instability and causes a partially unstable stability phase. Especially during an instant manoeuvre on an inclined road, a sudden momentum change may occur which leads to a high risk of overturning (Newton, 1999). The corresponding stability zone for Phase 1 instability is given in the Figure 1.b. With the activation of one of the bumpstops, the relative instability between the body and the axle is restrained and the stability zone of the tractor is now determined by a quadrilateral since the relative movement between the axle and the body is completely restricted. In this phase, the overturning moment occurs around the edges of the trapezium formed by the contact point of the three wheels lying in the same plane and the pivotal joint. This instability phase is called as Phase 2 instability (Previati et al., 2014).

Both stability modes work depending on the certain parameters of the tractor. In other words, the angle at which the instability begins is directly related to physical properties of the tractor. Hence, the mechanical properties of the vehicle that affect its dynamic behaviour, such as wheelbase, track width and mass, must be known to be able to evaluate the stability behaviour of the tractor. Within the scope of this study, a vineyard-orchard tractor with a narrow track-width is examined. This tractor has a rigid body with a pivotal front axle and is powered by a 55 kW, 3-cylinder engine. The characteristics of the tractor in question (Figure 2) are summarized in Table 1.

Table 1. The basic dimensions and the mass of the examined tractor New Holland TN75V

Properties	**Symbol**	**Value**
Mass	m	2355 kg
Front trackwidth	ft	940 mm
Rear trackwidth	rt	860 mm
Wheelbase	wb	2060 mm
Front tire size	-	280/70R16
Rear tire size	-	360/70R28
Pivot angle limit	-	±5°

In addition to these features, the CoG position of the vehicle must also be known. ISO 789–6 determined some guidelines for measuring CoG positions of agricultural vehicles. To determine the lateral and longitudinal position of it, the tractor is positioned in a flat surface and tire forces are measured by force sensors. For the vertical position, one of the axles is positioned elevated than the other and by using basic moment equations, the exact value can be obtained. During the measurements, tire pressures should be within nominal values and fuel tank should be full (ISO, 1982).

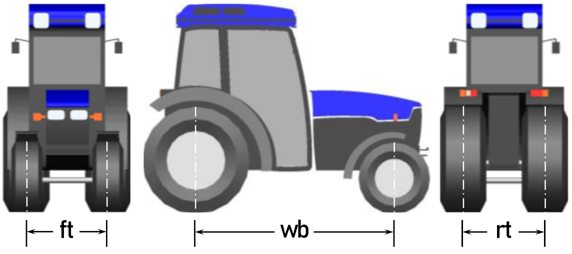


Figure 2. Basic dimensions of the tractor

The test-rig, as depicted in Figure 3.a, currently available at AFILab facilitates CoG measurements performed. The platform has a load capacity of 10 tons and its dimensions of approximately 6x4 meters allow a wide variety of tractors to be tested. The platform, which can rotate up to ±175° of β orientation angle around the vertical axis, can successfully perform an α tilt angle of up to 55°. While the 0° orientation angle gives longitudinal and forward tilting, +90° represents right and -90° left tilting scenarios. These rotational DoFs of the platform are depicted in the Figure 3.b. To prevent the tractor sliding on it, the platform surface has a grid structure which increases the grip capacity of the tires on the platform surface. The test platform is divided into four sections, one for each wheel. The vertical load measurements of the wheels can be easily performed thanks to the load cells located under each section. Vertical level difference between the axles is satisfied by this tilting ability of the platform as required by ISO standards. In order to ensure the accuracy of the CoG measurement results, a series of experiments were carried out by incrementally changing the orientation angle of the platform. The vertical force values of the wheels were measured for different orientation angles, and the CoG position is calculated according to ISO standards as a result of a series of mathematical operations by using wheel loads for each step (ISO, 1982). The CoG value is considered as the average of these results to ensure the accuracy of its real position. The detail of the method is widely explained in (Carabin et al., 2023).

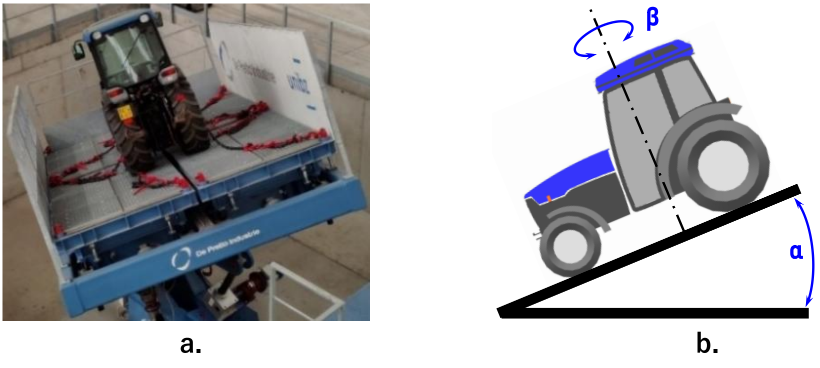


Figure 3. **a.** Stability test-rig and **b.** its rotational degrees-of-freedom

Tractor stability is evaluated by lateral rollover tests as defined by ISO 16231–2 standard (ISO, 2015). Nevertheless, since tractors operate in all orientations on sloped terrain, they are not only exposed to the risk of overturning in the lateral direction. Hence, it is of great importance to characterize the stability behaviour in each orientation scenario. However, when the impact of individual parameters needs to be examined separately, it is a very labour-intensive and time-consuming process. Using alternative methods that allow for preliminary analysis of specific parameters is quite essential. In addition, it is highly practical and useful to use such a method to estimate the effect of variables at the prototype stage. At this point, MBD analysis method becomes highly relevant to estimate the influence of a certain parameter in a short period of time. MBD is a method that mathematically models the relative motions and interactions of multiple interconnected bodies. It primarily examines dynamic and kinematic effects of the system variables by using mass, CoG and inertia values of all the bodies involved besides kinematics constrains among all the different bodies. Although it assumes all the system elements as rigid bodies since it does not consider mechanical and material properties of the elements, in these recent years, it also offers the possibility to analyse also elastic bodies in dynamic environments. The DoF of the bodies are determined by joints. Each object has three rotational and three translational DoFs when no boundary conditions are defined joints. To consider inertia effects, each body is considered as a 6-mass system consisting of two masses on each spatial axis. System modelling relies on the Newton-Euler or Lagrangian equations (Harty and Blundell, 2004). Adams, which is utilized in this paper, is a commercial software that is widely adopted particularly in vehicle design applications.

The last information required for MBD analyses was provided by determining the CoG position. Both the tractor and the platform geometries were composed in the Adams/View 2022.3 environment for the analyses. Realistically, the platform in the simulations allows for an orientation angle of up to ±180 degrees, while the front pivotal axle geometry acquires a rotational DoF of up to ±5 degrees. All system components were assumed to be rigid bodies. The PAC2002 tire model used in the analysis assumes the dynamic friction coefficient between the road and the tire as 0.9 by default on Adams environment. However, increasing the friction allows rollover analyses at a wider orientation range as it limits the sliding of the tractor on the platform before it reaches its instability angle. The “Magic Formula” used in this tire model calculations relates the slip angle to the tire deformation, i.e. the tire stiffness (Kuiper and Van Oosten, 2007). Therefore, increasing the friction coefficient to excessive amounts will considerably affect the results. Hence, the friction coefficient is accepted as 1. Unlike the actual-grid-designed platform surface, a flat surface was utilized in the simulations. Since the tractor wheels were secured to the platform using loose chains to ensure safety and prevent the complete rollover of the vehicle, the tractor in the simulations was also tied to the platform by ropes that did not exert any force until the moment the tractor overturned (i.e. when one of the wheels left the ground) which proves that using chains during the real experiments does not influence the test results. The ability of the MBD model to perform extensive and accurate tests is elaborated in detail in the cited reference (Karaca et al., 2024).

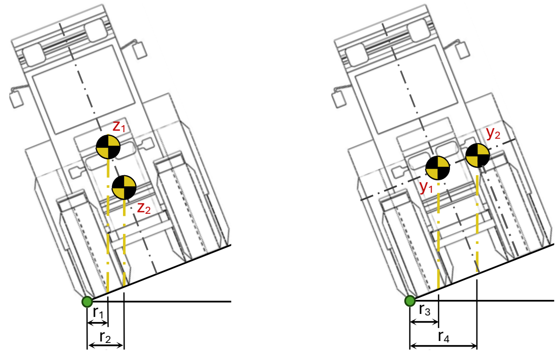


Figure 4. The representation of the effect of the CoG position on rollover moment for lateral instability in z (left) and y-axes (right)

Some implements are mounted symmetrically along the longitudinal axis of the tractor, while others are mounted laterally, resulting in considerable shifts in the CoG position. This is particularly important when operating on lateral or near-lateral slopes, where the instability is at the highest level (Previati et al., 2014). Implements like a front shredder, used to clear weeds and mounted at the front of the tractor, or the sprayer, used to spray vineyards/orchards and mounted at the rear, do not significantly alter the CoG laterally. In contrast, equipment such as the shoot remover, designed to clear weeds along the edges of vineyards and mounted on the side of the tractor, causes a lateral shift in it. The effect of CoG shift on the stability on different directions can be seen in Figure 4. Due to the symmetrical structure of the tractor in question, the CoG position without any implement is also nearly symmetrical. This lateral symmetry results in similar instability characteristic for both right and left tilting scenarios. The vertical position of the CoG is also as critical as the lateral position in terms of stability. As the vertical position increases, the distance to the stability axes will increase which amplifies the overturning moment for the same weight. In other words, for a certain lateral tilt angle, an elevated CoG position will lead to higher instability, as it reduces the distance to the support point. Given that the location of the CoG is the critical factor influencing its position is shifted in all three axes, and for each axis, 4 different scenarios were considered. It was shifted in x-direction by ±10% and ±20% of the wheelbase, in y-direction by ±5% and ±10% of the front trackwidth, and ±20%, -10% and +40% of the height of the real CoG position.

RESULTS AND DISCUSSION

For all these scenarios, MBD analyses were carried out in 5-degree increments across the entire orientation angle range of the tractor and the critical moment when the vertical force between either one of the wheels and the platform is zero has been identified. In simulations, when the tractor reaches a certain orientation angle (approaching front or rear longitudinal overturning, i.e., $\beta<\pm25°$ or $\beta>\pm135°$), it is not possible to measure overturning angle values since the tractor starts to slide on the platform before rolling over. In order to estimate the stability angle outside of these angle values, stability models other than the methods used in this paper should be utilized. Details of such a method are given in (Carabin et al., 2023).

Table 2. The CoG positions of all investigated scenarios (x, y, z)

Direction	Positive shift		Negative shift	
x	10% (1022, 11, 676)	20% (1228, 11, 676)	10% (610, 11, 676)	20% (504, 11, 676)
y	5% (805, 58, 676)	10% (805, 105, 676)	5% (805, -36, 676)	10% (805, -83, 676)
z	20% (805, 11, 811)	40% (805, 11, 946)	10% (805, 11, 608)	20% (805, 11, 541)
Real CoG	(805, 11, 676)			

All the CoG values of the scenarios can be seen in Table 2. Here, the values between indents represents the x, y and z coordinates of the CoG position according to the cartesian system in Figure 1.a respectively. The results obtained are depicted in stability maps that is commonly used to characterize tractor stability in Figure 5. Here, the radial coordinate α represents the rollover angle; the angular coordinate β represents the orientation angle. The +90° value of the β angle indicates rollover to the right, -90° to the left, and +180° to the backwards. Figure 5.a shows the results of the tests and MBD analyses for the real CoG value. Figure 5.b presents the effects of the changes in the x direction specified in Table 2. As can be clearly seen, similar change rate in forward and lateral instability observed while CoG approaches the rear axle. However, in the case that CoG approaches to the front axle, the effect of the percentage change is greater than the CoG change rate. Both forward and backward change affects the backward rollover instability lower than the forward or lateral rollover. Figure 5.c shows the effects of changes in the lateral direction. It was observed that these shifts in y-axis created the most dramatic effects compared to the other axes. For all change ratios, the change in stability increased more than threefold (e.g., an average of 15-18% stability change for a 5% CoG position change and an average of 30% stability change for a 10% CoG position change). Finally, Figure 5.d presents the effects of changes made in the z-axis on stability. It is observed that the effect of the change in the vertical direction decreases as the position of the CoG increases. For example, a 20% increase in height causes a stability decrease of approximately 20%, while a 40% increase in height does not exceed 33% stability decrease. However, when the CoG is lowered by 20%, a stability improvement of approximately 30% is achieved.

As confirmed by all scenarios, the highest risk of instability, i.e. the lowest rollover angle, occurs in orientations near lateral rollover. This proves that the most critical rollover risk is in the orientations closer to the lateral direction when the tractor is operating on sloped terrains, either with or without implements. The effect of the deviations in the longitudinal axis on the nearly forward rollover scenarios is greater than on the nearly backward orientations. However, these results are only accurate for steady state conditions (i.e. constant speed, stationary, etc.) and the load transfer between the axles caused by sudden accelerations while climbing a hill may improve the possibility of backward rollover different than these rates. While using a laterally asymmetrical implement, keeping the implement higher than the tractor on the direction of the slope improves the stability of the tractor compared to the no implement version. Similarly, using the implement lower than the tractor level dramatically decreases the stability.

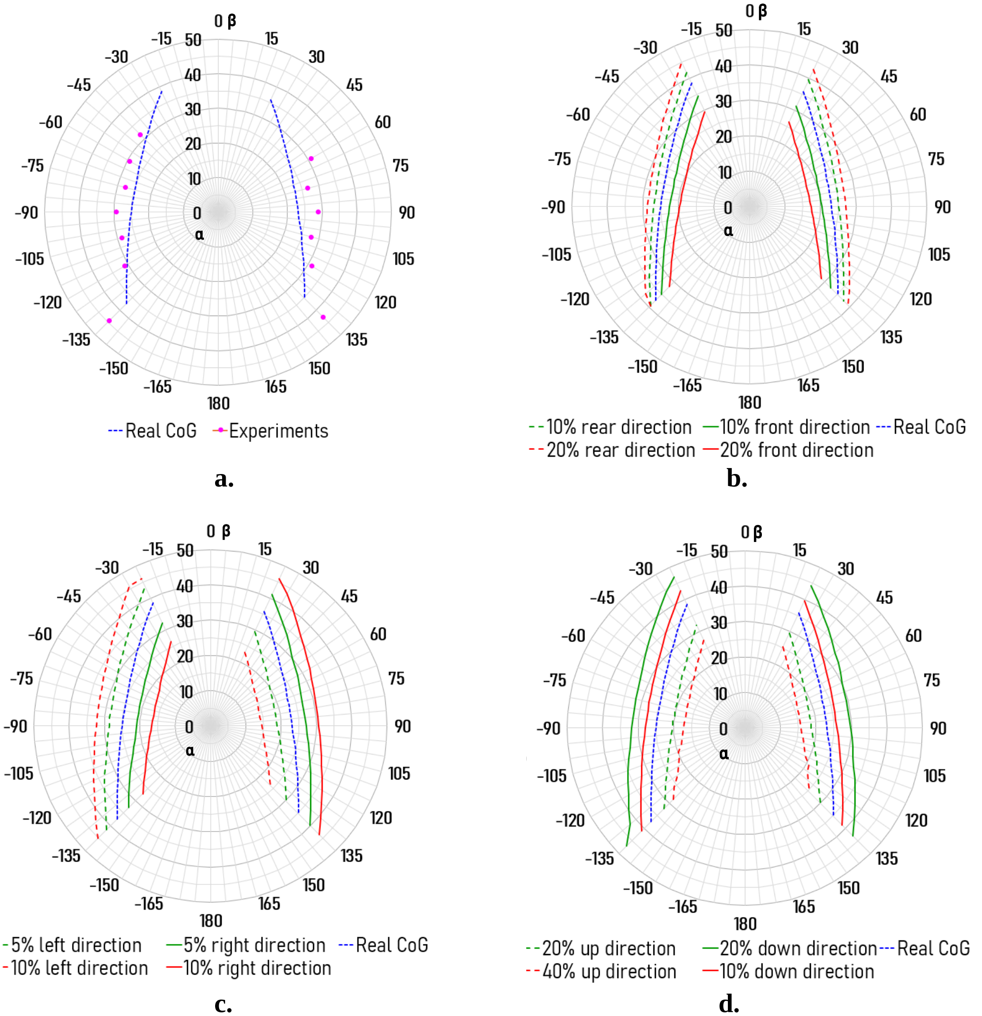


Figure 5. Stability map comparisons of the **a.** MBD model and experiments, **b.** CoG position change in x-direction, **c.** in y-direction and **d.** in z-direction

CONCLUSIONS

This study aimed to evaluate the rollover stability of tractors by analysing the effect of the implements on the CoG position. Within the scope of the study, the effects of changes in the CoG position on the rollover stability of the tractor were investigated by an MBD model whose accuracy was confirmed in a previous study. Rollover behaviours of a tractor at all orientation angles were evaluated in addition to the rollover tests defined in ISO standards. It was observed that changes in the CoG position, especially lateral shifts, created the most dramatic effects on stability. A 5% CoG shift in the lateral axis caused an average change of 15-18% in stability, while a 10% shift created effects of up to 30% in stability. Similarly, increasing the CoG in the vertical axis affected stability parabolically related to the shift range. The rollover risk reached its highest level in all scenarios, not during full lateral rollover, but in regions close to this situation. The use of MBD analysis has made it possible to quickly and effectively evaluate the effects of changes in the CoG position on the stability of the tractor. This method is very useful and practical, especially for estimating the effects of design parameters at the prototype stage. The findings provide a comprehensive tool for evaluating the rollover performance of agricultural machinery by using both experimental and numerical methods. These approaches can lead to significant improvements in both safety and efficiency.

ACKNOWLEDGEMENTS

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50. ACTUAL TASKS ON AGRICULTURAL ENGINEERING

Original scientific paper

LOAD ESTIMATION ON THE WHEEL OR ON THE AXLE OF AN AGRICULTURAL VEHICLE, BASED THE VARIATION OF THE STRAIN IN THE RIMS

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ABSTRACT

The article presents a possible solution for controlling the stability of vehicles, based on the information received from strain sensors mounted on rims. The solution is part of the modern solutions category for electronic control of vehicle stability, very widespread at present in the field of automobiles and, in our case, with special reference to vehicles and agricultural units. The following are presented: a structural simulator for the optimal choice of mounting locations for deformation sensors, the method of calculating the reaction forces on wheels using the signals of the strain sensors, the hypothetical form and the selection of the essential information from the signals coming from the sensors in variable speed travel, the method of estimating the risk of loss of stability and a scheme of the system of assisting and controlling the stability of the vehicle. There are also a number of developments necessary to define and put such a system on vehicles.

Keywords: *vehicle, stability control, agricultural machines*

INTRODUCTION

According to Stoicescu (1986), the manoeuvrability of a vehicle is defined as the whole of its qualities that characterize the possibilities to change, in a stable way, the direction of movement and the trajectory of the steering point, according to the requests of the driver. For a vehicle to be manoeuvrable, it must be and remain stable during driver manoeuvres. This means that the responses of the vehicle to possible road (travel) disturbances are reduced, thus also reducing the sensitivity of the vehicle to control. According to Untaru et al. (1981), in the language of transport specialists, the stability of vehicles means the ability of the vehicle to withstand sliding, skating, skidding and turning. The notion of dynamic stability of vehicles is used in mechanics and characterizes the behaviour of the vehicle on a desired trajectory under conditions of application of disturbances (stability in the Leapunov sense, for example Lazăr (1979)).

Improving the stability of vehicles is an activity of more than a century old, which contributes to the increase of the driver control on the vehicle and to the traffic safety. One way to solve these problems is to exploit the kinematic and dynamic relationships, starting from the general statements to in-depth relationships, by optimizing components, devices, introducing additional devices, etc., (Untaru et al., 1981; Sireteanu eta al., 1981; Karnopp, 2013; Rajamani, 2012; Eaton et al., 2009; Werner et al., 2020). Increasing the speed in traffic or the productivity of cars working on rough terrain (more or less), caused the first type solutions to be exceeded and replaced with stability control solutions by assisting the travel regime, i.e. the real-time control of the operating parameters of the vehicle. This second solution involves the use of appropriate sensors, which provide information convertible into a calculation system in decision and warning parameters for the driver. It is reached the level of electronic vehicle stability control (ESC) or electronic stability program (ESP) or dynamic stability control (DSC), which is a computer technology that improves vehicle stability by detecting and reducing traction or steering losses (Rédl et al., 2014). Some solutions go up to the automatic control of the vehicle, without human intervention, which has been achieved. The solution suggested by us in this article is part from the second category of solutions, and is refer especially to agricultural machines and aggregates, a solution that goes only until the warning stage on the level of risk of losing stability.

The study of vehicle wheel rims using complex numerical methods is already a routine operation in designing these basic elements of the means of transport industry. The basic problems studied are the behaviour of the wheels from the point of view of the resistance of the materials and the resistance to fatigue (Biriş et al., 2011; Panda et al., 2016; Machave et al., 2015; Satyanarayana and Sambaiah, 2012; Venkateswara and Dharmaraju, 2014). Also for wear analysis, wheel force sensors are used (Yan et al., 2018). For automobiles, concerns such as those described in this article are recent (Garcia-Pozuelo et al., 2017a; Yunta et al, 2018; Garcia-Pozuelo et al., 2017b; Mendoza-Petit et al., 2019; Ute et al., 2015), the deformation sensors can be mounted not only on the wheels but also on the inside of the tires. In the United States, a solution similar to that suggested, is already patented (Neuman, 2018). Obviously, the installation of such sensors can also be done on the deck, in the vicinity of the wheel contact or on the corresponding suspension of the wheel, if it exists. An alternative solution for wheel load control can also be tried using tire pressure sensors (Mendoza-Petit et al., 2019; Ungureanu et al., 2015; Ungureanu et al., 2017). For tire monitoring, there are relatively recent solutions, which use fibber optics (Roveri et al., 2015; Wang, 2023). For railway rolling stock, similar concerns appear, for example, in Bracciali and Folgarait (2004). Models of the type built more complex, partially, were considered in Cârdei (2019) and Yan et al (2022).

Appreciations regarding the limits of the measuring range with satisfactory sensitivity for strain sensors are found, for example in Agilent Technologies (1999). In Garcia-Pozuelo et al. (2017) is work with deformation sensors capable of measuring between -5000 and 5000 με. In Yunta et al. (2018) and Garcia-Pozuelo et al. (2017), deformation sensors with a resolution of 0.001 με are used.

MATERIALS AND METHODS

To estimate the behaviour of the strain field in the wheels of the vehicle, in this article we consider a simple structural model, whose components are the axle and the two wheels corresponding to it. Because we are interested, first of all, the road vehicles, the model of the wheels are constructed of two flat plates in the form of a circular crown. The inner plate, which connects the axle to the outer plate, shapes the rim. The outer plate shapes the working tire as a whole with the pressure air in it.

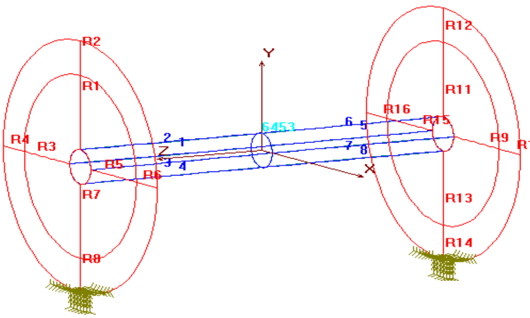

Figure 1. The structural model of the axle with wheels (rims and tires)

Table 1. Specifications on the structural model in figure 1

Component	Index in the structural model	Thickness, mm	Geometric type	material properties		
				E, N/m^2	ν	ρ, kg/m^3
Axle	Surfaces 1, 2, 3, 4, 5, 6, 7, 8	15	surfaces	$2.1 \cdot 10^{11}$	0.3	7850
rims (left, right)	Regions R9, R11, R13, R15; R1, R3, R5, R7	5	regions	$2.1 \cdot 10^{11}$	0.3	7850
tires (left, right)	Regions R10, R12, R14, R16; R2, R4, R6, R8	150	regions	$9.5 \cdot 10^{5}$	0.375	125

The physical properties of the materials from which the model components are built appear in table 1. The properties of table 1 characterize ideal linear, homogeneous and isotropic elastic materials. For the axle and rim the material is metallic. As for tires, these are composite materials that are difficult to describe in the complicated terms of this category of materials (natural and synthetic rubber, reinforced with metallic or plastic fibbers, and a high-pressure air volume). We preferred the description in table 1, assuming the linear elastic behaviour in the request interval that interests us. For the study of the tires, especially under running conditions, special models are built, whose properties result from very complex experimental studies. Generally, the linear behaviour is not characteristic of the tires throughout the request range (Untaru et al., 1981).

The structural model is fixed by cancelling all six components of the relative displacement field, as in figure 1. The length of the curves on which the seven completely blocked knots are inserted corresponds to the long axis of the tire contact patch (approximately 14 cm). The load is only of inertial type: own mass of the structure (110 kg) and a useful mass load (2000 kg), in nodal element 6453, visible in figure 1. In the case of rest or rectilinear displacement with constant speed, the option of gravitational field analysis is applied. In the case of the movements in the curve and / or accelerated, the same option is applied, maintaining the gravitational acceleration and introducing new components of the acceleration. The structural model contains 6453 elements and 3306 nodes, distributed like as shown in the table 2.

Table 2. The distribution of elements and nodes on the components of the structural model

Components	Elements	Nodes
axle	1-1280	1-660
rims	4193-6452	2445-3306
tires	1281-4192	661-2444
Authorised mass limit	6453	6

Static loading

Static loading is the reference load for the vehicle relative to the axle for which the calculation is made, i.e. the recommended load from the manufacture. For our generic case, it is assumed that the reference load is the one described numerically, above. For this data, the structural analysis program used: COSMOS / M 2.8 correctly calculates the structure mass and the total mass obtained by adding the load distributed to the middle of it. Table 3 gives the vertical reaction forces at the support points of the wheels (contact with the rolling path).

Table 3. Reactions in the nodes in the contact patch of the wheels

Wheel	nod	Vertical reaction force (Oy), N	Lateral reaction force (Oz), N
right	1138	2192.38	-10.91
	1137	1270.67	-0.50
	1136	1161.42	-0.39
	1135	1082.60	-0.34
	1384	1164.26	-0.56
	1383	1258.96	-1.38
	1382	2219.97	-6.59
Total right		**10350.26**	**-20.67**
left	2035	2219.97	6.59
	2036	1258.96	1.38
	2037	1164.26	0.56
	2038	1082.60	0.34
	2216	1161.42	0.39
	2217	1270.67	0.50
	2218	2192.38	10.91
Total left		**10350.26**	**20.67**
Total axle		**20700.52**	**0.00**

The centre of mass of the structure is located at the coordinate point: X_G=0 m, Y_G=0.07109 m, Z_G=0 m. The tread level corresponds to the plane Y=-0.4 m. The position of the centre of mass at a distance of only 0.47109 m from the road, favours the vehicle and we expect a large lateral acceleration to be necessary to overturn the vehicle.

Loads with lateral acceleration

Loads with lateral acceleration field simulate the behaviour of the axle (wheels and axle) in turns. It can be estimated thus, how the state of deformation in the wheel rims changes depending on the intensity of the lateral acceleration applied. With this information available, one can choose the optimal area for the deformation sensors to be located, so that with the help of the sensor indications a warning of risk of overturning or skidding can be issued.

Table 4. Vertical and lateral reaction forces in the two wheels of the axle

Lateral acceleration, a_z (axis Oz), m/s^2	Vertical reaction, R_{yd} (Oy), right wheel, N	Lateral reaction, R_{zd} (Oz), right wheel, N	Vertical reaction, R_{ys} (Oy), left wheel, N	Lateral reaction,, R_{zs} (Oz), left wheel, N
0	10350	0.0	10350	0.0
1	11077	-1075.9	9619	-1034.3
2	11807	-2130.8	8868.4	-2089.4
3	12540	-3186.7	8160.3	-3144.4
4	13269	-4241.2	7430.8	-4199.8
5	13999	-5295.6	6701.1	-5254.4
6	14731	-6351.1	5970.2	-6759.9
7	15460	-7406.6	5240.5	-7365.4
8	16190	-8460.8	4510.8	-8420.3
9	16921	-9516.3	3780.8	-9474.7
10	17649	-10570.8	3050.9	-10531.1
11	18379	-11606.6	2320.9	-11586.1
12	19109	-12680.6	1591.0	-12640.1
13	19839	-13736.5	861.1	-13696.0
14	20569	-14790.5	131.14	-14750.9
15	21298	-15846.4	-598.71	-15805.8

Table 5. The values of the radial and tangential strain in elements located in the high intensity area on the right rim and on the left rim

Lateral acceleration, a_z (axis Oz), m/s^2	**Strain in element 5038**		**Strain in element 5887**		**Recommended locations for placement of strain sensors**
	ε_x	ε_y	ε_x	ε_y	
0	0.000016	0.000010	0.000016	0.000010	In the first 10 cm under the axle, radials (Oy) and tangential (Ox), on the rim.
1	0.001213	0.000331	-0.001190	-0.000310	
2	0.002414	0.000651	-0.002391	-0.000631	
3	0.003615	0.000972	-0.003592	-0.000951	
4	0.004817	0.001292	-0.004793	-0.001271	
5	0.006018	0.001613	-0.005995	-0.001592	
6	0.007219	0.001933	-0.007196	-0.001912	
7	0.008420	0.002253	-0.008397	-0.002233	
8	0.009622	0.002574	-0.009598	-0.002553	
9	0.010820	0.002894	-0.010800	-0.002874	
10	0.012020	0.003215	-0.012000	-0.003194	
11	0.013230	0.003535	-0.013200	-0.003515	
12	0.014430	0.003856	-0.014400	-0.003835	
13	0.015630	0.004176	-0.015600	-0.004156	
14	0.016830	0.004497	-0.016810	-0.004476	
15	0.018030	0.004817	-0.018010	-0.004796	

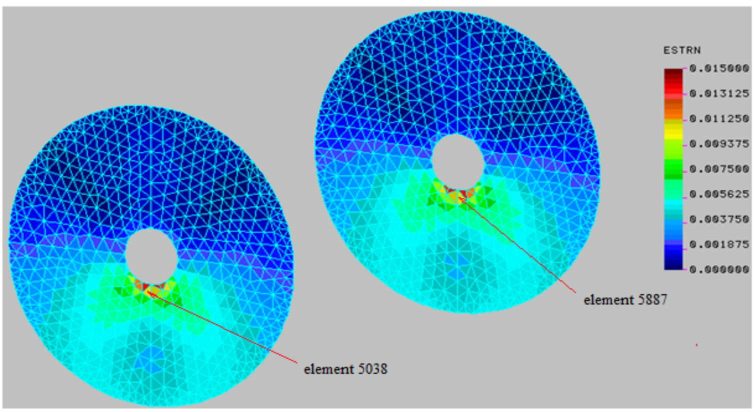

Figure 2. Typical distribution of the specific deformation in the two rims (the case of lateral acceleration with the value of 15 m / s^2)

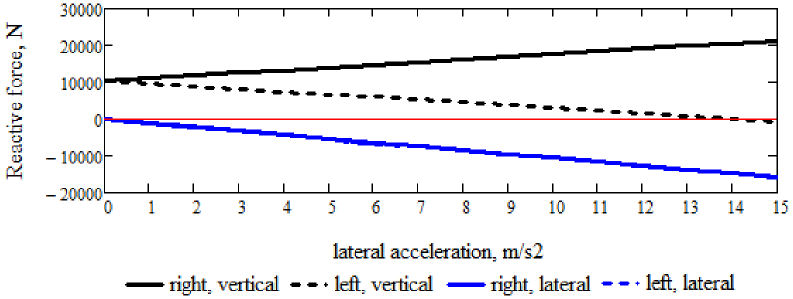

Figure 3. Dependence of the reaction forces by the lateral acceleration

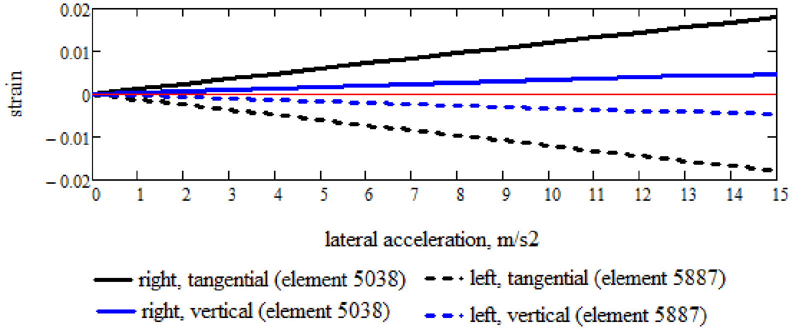

Figure 4. Dependence of the strain by the lateral acceleration

RESULTS AND DISCUSSION

Useful results in the field of vehicle stability

Direct relationships between the dynamic parameters of the vehicle

It is easy to observe the linearity of the relationships found by numerical simulation (numerical experiment) on the structural model described in Tables 1-5 and graphically represented in figures 2 and 3. These are direct consequences of the structural model characterized entirely by linear laws (linear elastic materials and deformation equations of the linear-elastic continuous body model). The introduction of some nonlinearity in the calculation (especially regarding the tires) would require a considerable experimental effort and a pronounced particular character for the model. For now, suppose that we can issue a risk forecast working within a linear model. However, the simulation technique we give in this article is similar to the calibration technique of a real model, in which the certain nonlinearities will be processed in the same way in order to obtain the stability control of the vehicle. Using the results of the numerical experiments (simulations) in chapter 1, the following functions are obtained by linear interpolation:

$$R_{ry}(\varepsilon_{rx}, \varepsilon_{ry}) = 10329.23 + 134989.27\varepsilon_{rx} + 1772039.07\varepsilon_{ry} \quad (1)$$

for the normal reaction force on the right wheel, depending on the strain indicated by the strain sensors mounted on the rim of the same wheel in the optimal area (table 5, element 5038), respectively:

$$R_{ly}(\varepsilon_{lx}, \varepsilon_{ly}) = 10325.58 + 119705.13\varepsilon_{lx} + 1827909.63\varepsilon_{ly} \quad (2)$$

for the normal reaction on the left wheel, depending on the specific deformations indicated by the strain sensors mounted on the rim of the same wheel in the optimal area (table 5, item 5887). Similar formulas are obtained for the lateral thrust forces that appear at the contact between the wheels and the rolling path due to the action of the lateral acceleration:

$$R_{rz}(\varepsilon_{rx}, \varepsilon_{ry}) = 63.17 + 1739150.49\varepsilon_{rx} - 9812347.24\varepsilon_{ry} \quad (3)$$

for the right wheel, respectively:

$$R_{lz}(\varepsilon_{lx}, \varepsilon_{ly}) = 125.15 + 7211396.67\varepsilon_{lx} - 23750130.47\varepsilon_{ly} \quad (4)$$

for the left wheel. By the same procedure the lateral acceleration can be calculated, as a function of the indications of the strain sensors, in case this acceleration is not known:

$$a_l(\varepsilon_{lx}, \varepsilon_{ly}) = -0.027555 + 171.39669\varepsilon_{lx} + 2478.075427\varepsilon_{ly}. \quad (5)$$

The calculation of the values of the dynamic parameters involved in the calculation of the stability of the vehicle must be done with great care, considering permanently that we do not have the guarantee of the bijection between the set of values of these parameters (the dynamic state of the vehicle) and the state of deformation in the rim. Therefore, the possible use of functions with several arguments for formulas (1) - (5) must be considered. This means that, for example, the lateral acceleration could be modelled as a function of the eight indications of two marks placed on four wheels or even more. We also do not exclude the placement of more than two brands on each rim.

Through the physical calibration experiments, the functions (1) - (4) can be appreciably different, especially if one reaches the non-linear operating area of the tires.

If in the indicated locations (the areas covered by elements 5038 and 5887), the strain sensors are mounted and the data recorded, a fast data processing with the help of the functions (1) - (4), leads to the knowledge of the loads on each one two wheels. With these data and the knowledge of the state of the tread surface, as well as the limits imposed in force, for example, warnings of risk of loss of stability can be issued.

Expectations on the form of signals received from strain sensors

The simulation or numerical experiment described in first part is based on a static model. In dynamic mode, the wheels and consequently also the rims undergo complex movements (orthogonal transformations) that also contribute to the deformation state, but essentially contribute to the shape of the signal emitted by the strain sensors. During a rotation of the wheel, the strain sensor goes through a lot of values, of which the interest for stability is the maximum absolute value. Therefore, it must be taken into account that the signal processor will permanently take over the maximum absolute values of the sensors and on these will perform the calculations of the risk of losing stability. About the way the signal curve provided by the deformation sensors looks, it is difficult to make a hypothesis, especially as the speed of rotation of the wheel can vary, sometimes even very much. For these reasons, we consider that exact aspects of the phenomena can only be clarified by experience, and the exposition in this chapter is only an attempt to anticipate, by the theoretical nature.

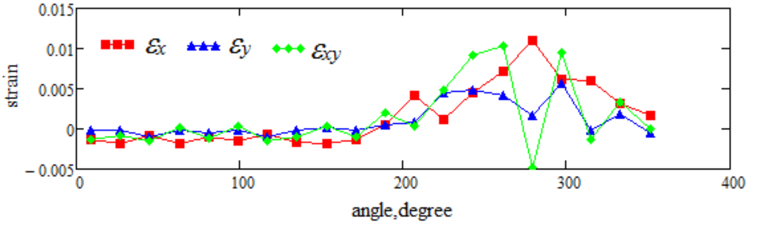

Figure 5. Distribution of the three non-null components of the strain tensor, in the optimal area of placement of a deformation sensor, around the axle

When the vehicle is moving, the strain sensor travels along a generally non-circular path (due to wheel deformation, especially tire deformation), indicating a number of strain values. Generally, we expect these values to take absolute maximum values when the sensor is located between the centre of the axle and the centre of the tire contact area with the tread path. To estimate the values indicated by the strain sensors, when they travel the above-mentioned trajectory around the centre of the axle, we used the structural model defined in chapter 1. The results are shown graphically in Figure 4. These results correspond to a static regime of deformation of the wheel. For simplicity, we assume that the results differ negligible from those obtained when the vehicle moves rectilinearly with the slow constant speed, the speed we will call, the calibration speed, v_c. Obviously, these simplifications can be a serious impetus for considering a dynamic, complex, possibly nonlinear model. We do not adhere to this option because it requires a lot of information that can be obtained only experimentally, with very high efforts and low certainties. On the other hand, the structural model (dynamic or static) should be subjected to a serious analysis of the convergence of the results (Kline, 2011; Zhao et al., 2019; Čiegis and Dapšys, 2022), knowing that the method of the finite element does not excel in precision and especially if it is desired that the results reach prediction rank. For a very complex theoretical model, the experiment would be mandatory involved in two stages: estimating the model constants and then, validating the model. In another order of ideas, at a higher level, is raised the critical problem of the bijection of correspondence (Ştefănoiu et al., 2012; Cârdei et al., 2012) between the causes that produce the state of deformation in rims and the set of values indicated by the system of strain sensors. From a physical point of view, if the correspondence cause-effect bijection (one-to-one application) does not work, it is possible that a decision to lose stability is made, when it is not the case, either, the decision is not issued and yet the phenomenon of loss of stability occurs. Obviously, this problem must also be taken into account in the case of a priority experiential approach to the problem of vehicle stability. As a result, we opt finally, for the experimental study, only oriented and initially guided by an elementary theoretical model.

In order to be able to emit a prediction on the signals coming from the strain sensors located on the rims, we collected the average values in space, of the specific deformation components, $\varepsilon_x, \varepsilon_y, \varepsilon_{xy}$ in the optimally chosen areas. These were graphically represented in Figure 4, and then interpolated by Fourier series. It was assumed that the values shown in Figure 4 were obtained in a low speed calibration movement, $v_c = 1\ m/s$. For example, for the component ε_x, the next formula is obtained:

$$\varepsilon_x(\alpha) = \frac{a_{x0}}{2} + \sum_{k=1}^{n_f}(a_{xk}\cos(\omega_k\alpha) + b_{xk}\sin(\omega_k\alpha)) \tag{6}$$

where α is the radius angle of the centre of the strain sensor with the horizontal of the forward direction (Ox axis, Figure 1), n_f is the number of terms considered in the Fourier series development (6), and ω_k is the string of the pulses (frequencies) considered in the Fourier development (6):

$$\omega_k = \frac{2k\pi}{T} \tag{7}$$

in our case, T is even 2π. The coefficients a_{xk}, b_{xk} are given in Table 6.

Table 6. Fourier series development coefficients for the ε_x component of the strain tensor

k	a_{xk}	b_{xk}
0	0.00315220	0.00000000
1	0.00048179	-0.00444650
2	-0.00179604	-0.00062252
3	-0.00055812	0.00009317
4	0.00040499	0.00057044
5	0.00009641	-0.00085083
6	-0.00055858	0.00009605
7	0.00017070	0.00018483
8	-0.00003368	0.00014430
9	0.00084792	0.00024361

For comparison, the samples collected according to the solutions of the model defined in chapter 1 and the Fourier series of this signal, are graphically represented in figure 6. It is observed that the approximation is sufficiently good and it takes over the extreme values, which are of particular interest in the control of wheel and axle loading.

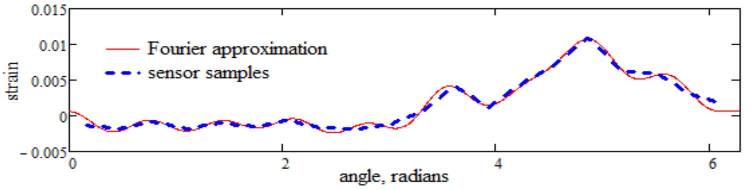

Figure 6. Comparative representation between the sampled signal from a (virtual) strain sensor and the Fourier approximation of the signal

Let R_d now be the dynamic radius of the wheel and ν_c the frequency of the sensor signal obtained when calibrating with the travel speed v_c:

$$\nu_c = \frac{v_c}{2\pi R_d}. \tag{8}$$

With these details, the frequency of the deformation sensor signal mounted on the rim, at a certain speed, time dependence, $v(t)$, and becomes:

$$\beta(t) = \frac{v(t)}{v_c}\nu_c \tag{9}$$

frequency, as observe, variable in time. With (6), (8) and (9), the hypothetical signal that will be obtained from a strain sensor, located on the rim, will have the next form:

$$\varsigma_{\varepsilon x}(t) = \varepsilon_x(2\pi\beta(t)t) \tag{10}$$

The Figure 7 graphically shows the influence of the speed of movement of a vehicle on the signal emitted by strain sensors located on the rims, the influence being a hypothetical one at this purely theoretical stage of development.

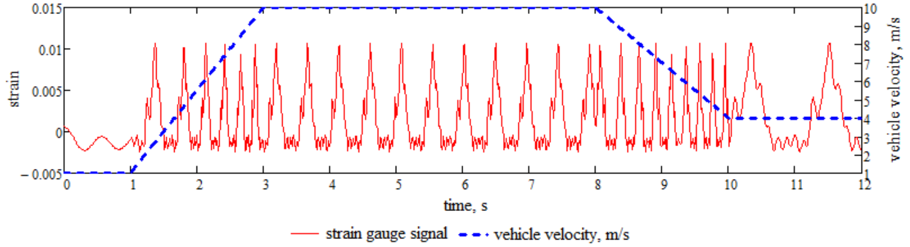

Figure 7. The influence of the speed of the vehicle's movement on the signal emitted by the sensors located on the rims

Figure 8 graphically shows the influence of the speed of movement of a vehicle on the frequency of the signal emitted by deformation sensors located on the rims. It can be observed that the travel regime was chosen so as to contain moving parts with constant speed, acceleration and deceleration portions. It is observed that the frequency of the signal received from the sensor is constant on the constant speed portions (but differs for different speed levels), increases on the acceleration (positive) portions and decreases on the deceleration portions. The simulation is done on a section of straight road with a length of approximately 84 m, considering the dynamic radius 0.75 m.

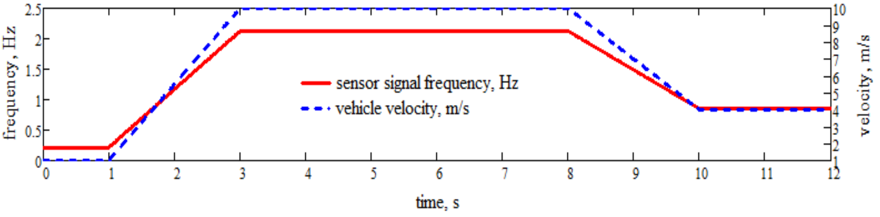

Figure 8. Influence of vehicle speed on the frequency of the signal emitted by the sensors located on the rim

Obviously, there is the possibility that the signal intensity of the deformation sensors will suffer the variations with the intensity of the rectilinear displacement speed, but these can be noticed on dynamic structural models and possibly considering some non-linear properties of the tire. Acceleration and deceleration can also produce additional effects in the signal intensity of the sensors, effects that can be simulated also on dynamic models, but very expensive. The presence of shocks caused by passing the wheels over disruptive objects on the road may induce the generation of strain sensor signals, which may cause false warnings, or may induce opposite situations. The experiment and the simulation, of high resolution, the dynamics simulation, can to a certain extent eliminate these phenomena. The provision of filters to eliminate false warnings is a higher level activity, for the control systems already built. All the considerations made on the component ε_x, of the tensor of the specific deformation, are made similarly for the components ε_y and ε_{xy}.

Use of theoretical-empirical relationships in the process of monitoring the stability of the vehicle

Using the structural model defined in Tables 1-4 to estimate the values that the deformation sensors located on the rims of vehicles can indicate. Thus we found a connection with the wheel load (vertical and in the rolling plane). We used the simulation of the action of lateral acceleration fields, in order to estimate the turning or skidding. Using such results, simple relationships have been established that link the values of normal and transverse loads on wheels, with the maximum values of the signals from the sensors. We used the simulation with the structural model of the displacement to estimate the shape of the signal from the sensors. Now we know that if from the received signal we select the extreme values, we can estimate, in a range of fractions of seconds until to one second, the loads on wheels. By default, by comparing them with preset limits, a signal of risk of loss of stability can be given. The principle scheme is shown in figure 9. The main components of the system are grouped in five blocks shown in figure 9.

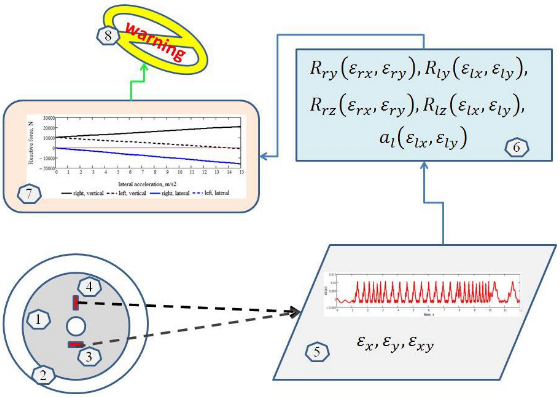

Figure 9. Principle scheme of the vehicle stability control system, based on deformation sensors mounted on the rims of the vehicle on wheels

1- rim; 2- tire; 3-strain sensor; 4- strain sensor; 5- data acquisition block; 6- calculation block for wheel load and acceleration; 7- control block and warning decision; 8- warning block

The first block is made up of the wheels (tires, rims and sensors mounted on the rims). This first block provides the signals to the second, formed by the data acquisition block. This block collects samples from the strain sensors, from the rims of all wheels. Because in the calculating the load forces on the wheels, only the maximum values indicated by the strain sensors are used, in this block a module for selecting the maximum values received from each sensor should be integrated. The selection module can also be included in the third block, its role being an intermediary between the main processes that take place in the second and third blocks. The third block (denoted by 6 in figure 8) consists of relatively simple calculations that give the values of the vertical and horizontal reactions on wheels as functions of the maximum values of the signals provided by the deformation sensors, according to the relations of type (1) - (4). Relationships can still be complicated, in the hope of increasing accuracy in estimating reactions. The reactions can be considered as functions of a greater number of arguments: from the minimum the main indications of the sensors on the corresponding wheel rim, to the maximum values of all the sensors on the wheel or on the axle, or even on all the wheels of the vehicle. The dependence of each component of the wheels reactive force on each sensory signal will be studied through the correlations between them in order to adopt rational and optimal computation relationships. The data calculated in the third block should be used to test the stability conditions in the fourth block of the system (number 7 in figure 9). When the conditions of stability approach the limit of the risk of losing stability, the fourth block emits a specific signal, transformed by the fifth block (number 8 in figure 9), into a video and audio signal for the driver.

An important problem will be that of the delay time of issuing the warning, in relation to the production of the risk phenomenon not allowed to lose the stability.

All the problems briefly described in this subchapter, the construction of each block and the modules, are separate chapters in works that will be developed if the proposed method has prospects of application. We also mention that the estimation of the signal frequency from the deformation sensors may be related to the speed of movement of the vehicle.

Using the calculated data starting from the maximum values provided by the strain sensors, in aim to evaluate the stability of the vehicles

According to (Untaru et al., 1971), in the general widespread acceptance, the *stability of the vehicle* means the ability of the vehicle to withstand slipping, sliding, skidding and turning.

Also in (Untaru et al., 1971), it is shown that, depending on how the movements occur with respect to the main axes of the vehicle, the *longitudinal stability* and the *lateral stability* are distinguished, each of them being able to refer to reaching the adhesion limit or to the overturning. The conditions of loss of stability are defined in terms of the normal and tangential reactions to the running path, i.e. in terms that the method presented in the previous chapters, them calculates directly from the data collected from the wheels of the vehicles on wheels.

Longitudinal stability of vehicles on wheels

According to (Untaru et al., 1971), the *longitudinal stability* of the vehicle is the ability of the vehicle to withstand longitudinal sliding or skidding as well as overturning in relation to a transverse axis.

Longitudinal stability when overturning

In (Untaru et al., 1971) (p. 211, (7.1)), for a two-axle vehicle, moving in the direction of the highest slope, the longitudinal overturning condition is that the reaction at one of the deck (usually the upstream one) will cancel. The relationships of type (1) - (4), calculated for both bridges, can detect the unauthorized approach of cancelling the total reaction on one of the decks. The rest of the relationships that appear in the specialized literature, regarding the longitudinal stability at the turning, are deduced from this condition. In the terms used in this paper the condition is expressed by the next equality:

$$R_y(\varepsilon_{rx}, \varepsilon_{ry}) = R_{ry}(\varepsilon_{rx}, \varepsilon_{ry}) + R_{ly}(\varepsilon_{lx}, \varepsilon_{ly}) = 0 \tag{11}$$

which must be made for one of the decks, in case of overturning. We noted with R_y, the reaction on the deck.

Longitudinal stability when skating or sliding

Also in (*Untaru et al, 1971*), and also for a vehicle with two axles, the rear being engines, the condition of lack of skating is:

$$R_x(\varepsilon_{rx}, \varepsilon_{ry}) = R_{rx}(\varepsilon_{rx}, \varepsilon_{ry}) + R_{lx}(\varepsilon_{lx}, \varepsilon_{ly}) \leq \varphi R_y(\varepsilon_{rx}, \varepsilon_{ry}) \tag{12}$$

where the forces having the index x are the longitudinal reaction forces on the wheels, and φ is the coefficient of adhesion between the tires of the wheels and the running path (considered here, hypothetically the same for all the wheels). The longitudinal reaction forces can be calculated, at least theoretically, in the same way as the vertical and lateral ones. The correlation between these and the signals of the deformation sensors must be studied very well.

The transverse stability of wheeled vehicles

According to (Untaru et al., 1971), the transverse stability is the ability of the vehicle to withstand sliding (transverse sliding) or transverse overturning, in relation to the right line joining the centres of the wheel contact spots on the same side of the vehicle.

The transverse stability at slip

When the reactions in the plane of the driveway reach the adhesion limit, under the effect of the transverse forces the skid starts to occur. According to (Untaru et al., 1971), skidding does not occur if:

$$R_{r1xz} = \sqrt{R_{r1x}^2 + R_{r1z}^2} \leq \varphi R_{r1y}, R_{r2xz} = \sqrt{R_{r2x}^2 + R_{r2z}^2} \leq \varphi R_{r2y} \tag{13}$$

for the overturning on the right side, the relationship for the left side is similar. Indices 1 and 2 represent the reaction forces that appear on the wheels on the same side of the vehicle (1-front, 2-rear).

Therefore, fundamentally, the condition of transverse stability at slip is put entirely in terms of reactions to the vehicle wheels. The only term to be estimated by the human operator and introduced in the calculation program is the coefficient of adherence. The automatic detection of the coefficient of adhesion is a problem in work already (Yunta et al., 2018; Singh and Taheri, 2015).

The transversal stability at overturning

According to (*Untaru et al, 1971*), the transversal turning occurs when the wheels on the same side of the vehicle begin to lose contact with the driveway. The authors define the overturning condition for a rigid vehicle, without suspension, also in terms of reactions to the vehicle's wheels:

$$R_{ry} = R_{r1y} + R_{r2y} \tag{14}$$

for the overturning on the left side, similar instead of r appearing the index l, for the overturning on the right side.

The consideration of the suspension contribution complicates things theoretically, being necessary to know some geometric and physical characteristics of the suspensions. In the case of agricultural vehicles, the suspensions are less important and often very rigid. However, in the calculation presented in the proposed model for the evaluation of the reactions on wheels and axles, the above mentioned characteristics of the suspensions automatically enter (due to the experiments on the real subject).

CONCLUSIONS

In addition to the conclusions obtained from the results, conclusions regarding the form of information that can be exploited for the purpose of monitoring the stability of vehicles, as well as details about the large amount of complementary results that can still be obtained for the same purpose.

First of all, it should be noted that, due to the rotation of the rim in motion, the signal generated by the specific deformation sensors will be received as a dynamic signal, partially quasi-periodic (periodically only for the sections of trajectory with constant speed, and rectilinear speed). Therefore, in order to use this signal for the purpose of obtaining a forecast of risk of loss of stability, effective and rapid processing is required to be able to issue the risk warning in time. For these reasons, the reception, processing and issuing of the risk forecast form a chapter that must be treated very seriously, separately.

The structural model presented in this paper is an elementary, generic one (a very general geometric and physical scheme, and not specific to a particular vehicle). This model shows that changes in vehicle dynamics produce changes in the state of deformation of the wheels. The changes in the state of deformation in the rims will be used to estimate the risk of loss of stability (skidding, overturning, loss or unevenness in traction) and to issue useful warnings to the driver of the vehicle for the purpose of restoring the proper road condition.

When a stability control system will be created, concretely, for a given vehicle, all the operations described in this article by simulation will have to be performed experimentally, and the dependency curves between variables will have to be deduced experimentally. The system will be calibrated for the given operating conditions (preset tire pressure, complying with the speed and acceleration limits imposed by the manufacturer, the certain geometry of the rim). Tire pressure matters a lot, with the possibility that in the vicinity of the stability loss points, the tire behaviour becomes nonlinear.

For now, the method proposed only theoretically (by simulation), shows that certain aspects of vehicle stability can be controlled and the risk of losing stability can be evaluated, using the indications of strain sensors mounted on the rims.

Advanced simulators for evaluating the information given by strain sensors located on rims

In order to evaluate the usefulness of the strain sensor information located on the wheels of the vehicle wheels, more complicated models can be developed than the one presented in this article. The purpose so far includes only the evaluation of the use of information from strain sensors located on wheels, in order to control the stability of vehicles on wheels. Among these general models, we mention:

M1 - model of two-axle vehicle, with the position of the known centre of mass (static, linear and non-linear dynamics);

M2 - vehicle model with more than two axles, with the position of the known centre of mass (static, linear and non-linear dynamics);

M3 - model of vehicle with trailer or train of vehicles (tractor plus two trailers), which are much more difficult as it is necessary to model as close as possible the reality of the connection between components (one overturning may cause the other overturning);

M4 - models of the type considered in the chapter 1, M1, M2 or M3, with tires and rims modelled structurally complex (curved surfaces, three-dimensional bodies).

Modelling and simulation must contain a convergence study that will specifically help to maximize the accuracy of the strain in the locations where the sensors are located.

The system of relations of data processing

The way we build the relationships that estimate the reaction forces is the same as the one presented briefly in this article, but it must be taken into account that in reality we could have at least two strain sensors on each wheel, so between eight and twenty, maybe even more signals, or arguments of the reaction functions. For this reason, based on simulation data (if possible experimental ones), the correlation between each reaction force at each wheel and all signals from all sensors should be estimated. Only those signals strongly correlated with the respective reaction will be retained as arguments for each component of the reaction.

Depending on the option of including manoeuvrability among the controlled stability properties, the steering angle sensor (with angular velocity and its angular acceleration) can also be considered.

Data processing systems that are obtained from strain sensors located on the wheels of the wheels

The data processing system proposed in the article can still be greatly improved. The fundamental study of this system will contain, however, the part of estimating its promptness that is, estimating the delay in time of the warning against the moment of measuring the specific deformation data that led to the achievement of limits of risk of loss of stability.

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50. ACTUAL TASKS ON AGRICULTURAL ENGINEERING

Expert paper

ENERGY CONSUMPTION STUDIES OF A MACHINE-TRACTOR AGGREGATE FOR SPRING PRE-SOWING TILLAGE

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ABSTRACT

The main agricultural soil-related operations carried out before sowing spring crops are early spring harrowing and pre-sowing with or without harrowing. In Bulgaria, pre-sowing is done with KPS or KPG cultivators or RAU cultivator-combinators which have spring-cultivator and active rotary working units and guarantee the structure of the plough layer is even and finely grained. For the realization of this technological operation, a cultivator for pre-sowing soil treatment "Lemken", model "Korund 8.900" has been imported and used for three years in our country. This machine is aggregated with tractors with a nominal towing capacity of 50 kN (John Deere 8R280). The efficient use of this machine-tractor aggregate required a comprehensive study of its energy consumption by applying the tensiometer method. With reference to this, this paper outlines the basic scheme of the experiments performed, the order and methods of determining the most important energy indicators, as well as the findings of this study. In addition, the study provides results as to the appropriate combination of the machines comprising the aggregate for spring pre-sowing tillage and ensuring the optimum towing and speed work modes when operating on sloping terrain, on carbonate chernozem soil.

***Key words**: energy indicators, tensometric method, combination of machines, cultivation*

INTRODUCTION

Throughout the world, as well as in our country, agricultural producers use various systems of pre-sowing soil operations against winter and spring crops. Spring pre-sowing operations aim to level the soil surface and to loosen the surface layer to preserve the moisture accumulated during the autumn-winter period, and to destroy the grown-up weeds. These operations also aim to create compacted seedbeds which provide good contact between the seeds and the soil and allow good access of water and air for rapid and simultaneous germination and growth of crop plants (Stoynev, 2004). Decisions about these treatments are made based on the specific characteristics of the area and the state of the field, and there are mainly two issues to consider, i.e. their timing and depth of implementation. The selection of appropriate machines to ensure quality work with minimum use of labour and production costs is also essential (Vassilev, 2012). The main processes carried out before sowing spring crops are early spring harrowing and pre-sowing tillage with or without harrowing (Todorov et al.,1982). In Bulgaria, spring pre-sowing tillage is done with KPS and KPG cultivators or RAU cultivator-combinators, which have spring cultivating working elements and active rotating working parts and guarantee the structure of the plough layer is even and finely grained (Beloev and Dimitrov, 2019).

Three years ago, in our country, the German company “Lemken” imported the cultivator System-Korund 900 L MARA, model “Korund 8” for pre-sowing tillage. This machine (Fig. 1) consists of a frame, a multi-bar, working sections for soil loosening, working sections (tines), a mechanism for regulating the depth of cultivation, rollers, and guide wheels. Marathon tines are used for spring pre-sowing tillage. There are 16 tines, spaced 98 mm apart, arranged in 4 rows per section (harrow) and are suitable for breaking up the soil. They can work at depths of 0,03 to 0,20 m. This machine, on the recommendation of the manufacturer, is aggregated with tractors having a nominal towing capacity of 50 kN (https://agronika.bg/kultivatori/lemken-korund.html).

However, combining these machines in an aggregate is not, unfortunately, based on scientific research about the power requirements of the energy-source machines available in our country. Agricultural producers rely solely on the recommendations of the agricultural machine manufacturers and the technical specifications of tractors or other energy-source machines currently used in Bulgaria.

Thus, the future mass application of this newly composed machine-tractor aggregate in agricultural in Bulgaria and its effective use necessitated that the University of Ruse “Angel Kanchev” carried out research in field conditions to study the appropriate combination of the machines in the aggregate with reference to their energy consumption and, therefore, ensure its optimal towing and speed working modes.

With reference to this, the purpose of this paper is to outline the procedure of conducting the energy consumption assessment of the machine-tractor aggregate for spring pre-sowing tillage, as well as to analyze the results obtained for its main energy consumption indicators.

MATERIAL AND METHODS

The energy consumption studies were carried out in 2023, on the agricultural lands of the town of Kubrat, Rousse region, on an already ploughed field before sowing, on carbonate black soil (chernozem) with an average slope of 5º (8.7 %). The research was done under conditions of soil moisture of 17.90 % in the 0 – 1,50 m layer and soil hardness of 14.78 kg cm^{-2} in the 0 – 0,40 m layer, according to the specific agrotechnical requirements for performing the technological operation of spring pre-sowing tillage.

The main energy indicators were determined for a machine-tractor aggregate consisting of a “John Deere 8R280” tractor as an energy source and a “Lemken“ cultivator, model “Korund 8.900” for spring pre-sowing cultivation (Fig. 1).

The tensiometer method was used to determine the energy indicators of the above-mentioned soil-protecting aggregate. The speed of movement of the aggregate was determined on experimental plots with length of 100 m. The scheme according to which the energy studies were conducted is shown in Figure 2, while the measurements of the required indicators were carried out by using a mobile tensiometer laboratory (PTL-1) with a set of multipurpose tensiometer units (Dimitrov and Beloev, 2016; Dimitrov et al.,2020).

Figure1. A machine-tractor aggregate consisting of a “John Deere 8R280” tractor and cultivator “Lemken“, model “Korund 8“.

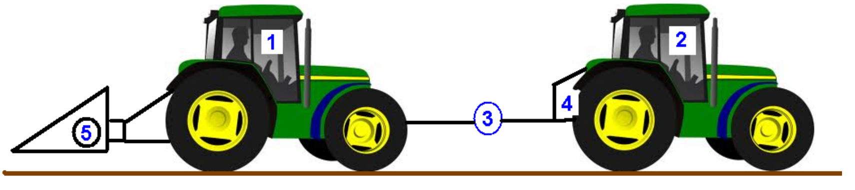

Figure 2. Scheme of the experiments determining the energy indicators:
1 – main tractor, 2 – second (towing) tractor, 3 – tensiometer unit for towing effort,
4 – sensor (converter) for the rotation frequency of the PTO, 5 – attached machine.

The total towing effort of the machine-tractor aggregate is measured with the help of a second (towing) tractor and the wheelspin of the main tractor. The wheelspin of the main tractor is also determined by the formula, specified in the Uniform Methodology for Conducting Tests (1976), namely:

$$\delta = \frac{N_{PTO1} - N_{PTO2}}{N_{PTO1}}.100 \ , \quad (1)$$

where:

δ – is the wheelspin of the main tractor, %;

N_{PTO1} – the number of pulses from the sensor attached to the PTO when the aggregate goes along the experimental plot with a working machine attached to it;

N_{PTO2} – the number of pulses from the sensor attached to the PTO when the aggregate goes along the experimental plot when the aggregate is in an idle time mode.

According to the technological requirements for the aggregate, three forward speeds were used for the calculations. A general energy consumption balance was drawn up where the consumed effective power of the tractor used during the work process was calculated according to Uniform Methodology for Conducting Tests (1976) by applying the following formula:

$$P_e = P_T + P_{PTO} + P_M + P_C + P_\delta + P_X \pm P_i\,, \qquad (2)$$

where:

P_e is e the effective power of the tractor engine, kW;

$P_T = F_T.V$ - the towing capacity of the tractor, kW;

F_T – the towing resistance of the attached machine, kN;

V – the average forward speed of the aggregate, m s^{-1};

P_{PTO} – the power for the PTO shaft, kW;

P_M – the power for overcoming the mechanical losses in the transmission, PTO and hydraulic drive mechanism, kW;

$P_\delta = \delta.P_B.10^{-2}$ – the power consumed by the wheelspin of the wheel drive mechanism, kW;

δ – the wheelspin, %

P_C – the power of the tractor's power take-offs, kW;

P_X – the power taken from the hydraulic drive mechanism, kW;

P_i – the power needed to overcome a slope, kW.

In our cases, particularly, because there is not a hydraulic drive mechanism and a longitudinal gradient, P_X and P_i are equal to zero.

In addition, the specific resistance per meter of working width in kN/m and the engine load factor of the used tractor were also calculated, according to the Uniform Methodology for Conducting Tests (1976) by using the following formula:

$$K_E = \frac{P_e}{P_n}.100\,, \qquad (3)$$

where:

K_E is the engine load factor of the used tractor, %;

P_e – the effective engine power, kW;

P_n – nominal engine power, kW.

In this case, the "John Deere 8R280" tractor, which is included in the machine-tractor aggregate for spring pre-sowing tillage, has a nominal engine power value P_n = 226.9 kW. A specialized computer application was developed and used to calculate and register the processed data of the general energy balance.

RESULTS AND DISCUSSION

The results of the energy-consumption studies of the soil-protecting machine-tractor aggregate for spring pre-sowing tillage that consists of a tractor “John Deere 8R280” and a cultivator “Lemken“, model “Korund 8.900“ are presented in Table 1. The analysis of the results from Table 1 show that this aggregate can operate on previously ploughed field, prior to sowing with a speed ranging from 6.84 to 11.16 km h^{-1} (1.9 to 3.1 m s^{-1}).

Based on the built-in gearshift range of the “John Deere 8R280“ tractor, the technological operation of spring pre-sowing tillage can be carried out with the studied aggregate in terms of the speed capabilities of this tractor. With reference to its towing and power capacity, the “John Deere 8R280” tractor is also suitable for being used in the aggregate since its maximum towing resistance when performing pre-sowing tillage on a ploughed field at a depth of 0.16 m reaches 17.40 kN. In comparison, the nominal towing resistance of this tractor is 50 kN. The energy balance shows that the nominal power of the tractor (P_n = 226,9 kW) is sufficient to perform this soil-protecting operation. On a ploughed field before sowing the maximum power consumption can reach up to 139.19 kW, with an engine load factor of 61.0 %. The wheelspin of the tractor reaches a maximum of 12.50 % and is within the permissible range of 17 – 18 % for wheeled tractors (Simeonov et al., 1986).

Table 1. Energy-consumption indicators of a machine-tractor aggregate for spring pre-sowing tillage consisting of a tractor “John Deere 8R280”and a cultivator “Lemken“, model „Korund 8“

№	Indicators	Units	Indicator values		
1	Gear shift		1	2	3
2	Forward speed	m s^{-1}	1.9	2.5	3.1
3	Towing resistance	kN	15.20	16.50	17.40
4	Towing capacity	kW	28.90	41.25	53.94
5	Wheelspin	%	12.10	12.40	12.50
6	Wheelspin power	kW	3.50	5.11	6.74
7	Resistance of the aggregate in an independent movement mode	kN	13.40	13.60	14.10
8	Power of the aggregate in an independent movement mode	kW	25.46	33.75	43.71
9	Power for mechanical losses in the transmission	kW	19.31	26.70	34.80
10	Effective power	kW	77.16	106.81	139.19
11	Engine load factor	%	34.0	47.0	61.0
12	Working width	m	9.0	9.0	9.0
13	Depth of tillage	m	0.12	0.14	0.16
14	Specific resistance:				
	- per 1 meter working width	kN m^{-1}	1.69	1.83	1.90
	- per unit of the layer cross section	kN m^{-2}	11.08	13.07	11.88

In contrast to the tensiometer method applied in this study, some authors use and research an interesting method for determining the specific fuel consumption of a tractor by building an artificial neural network model during the technological operation of deep tillage (Sager et al., 2024). This method takes into consideration important parameters such as tractor power, soil texture index, soil moisture, soil bulk density, etc. (Sager et al., 2024). However, it does not study and provide information about the energy consumption balance in machine-tractor aggregates for spring pre-sowing tillage.

The above-mentioned data, obtained from the tensiometer method used in our study, can also be utilised when it is necessary to combine machines in aggregates for spring pre-sowing tillage. With the proper selection of a power unit and a cultivator for performing this operation, optimum towing and speed range, low engine load factor of the tractor and acceptable wheelspin can be achieved.

CONCLUSION

Based on the conducted energy consumption studies and the obtained results, the following conclusions can be drawn:

The chosen energy source in the newly assembled machine-tractor aggregate consisting of a “John Deere 8R280” tractor and a cultivator for spring pre-sowing tillage “Lemken”, model “Korund 8.900” is suitable due to its towing capacity and power capabilities. Its maximum towing resistance, when preforming pre-sowing tillage on a ploughed field, reaches up to 17.40 kN, with a nominal value of 50 kN for this tractor. In addition, its maximum power consumption reaches up to 139.19 kW with an engine load factor of 61.01 %, when the acceptable wheelspin is up to 12.50 % in the speed range from 1.9 to 3.1 m s^{-1}.

The “John Deere 8R280” tractor and the cultivator “Lemken“, model “Korund 8.900” are properly combined in a machine-tractor aggregate in terms of energy consumption and this aggregate ensures optimum towing and speed of operation when carrying out the technological operation of spring pre-sowing tillage on the agricultural lands of the Republic of Bulgaria, namely carbonate black soil (chernozem).

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50. ACTUAL TASKS ON AGRICULTURAL ENGINEERING

Expert paper

THE ROLE OF MECHANIZATION IN INCREASING EFFICIENCY IN PRE- AND POSTHARVEST MUSTARD CULTIVATION

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ABSTRACT

Mustard is a widespread crop that is valued for its adaptability to different agroclimatic conditions and its economic importance for oil production, animal feed and culinary products. The growing demand for mustard and the need for more efficient production have highlighted the importance of mechanizing the entire cultivation process. This paper focuses on the role of mechanization in mustard cultivation, with particular emphasis on post-harvest handling, while also addressing sowing and harvesting processes. Techniques such as precision farming, specialized mustard harvesters and optimized sowing methods are examined for their potential to increase yields, reduce harvest losses and increase overall efficiency. The study will also investigate post-harvest methods, with a focus on mechanical drying and storage systems to maintain seed quality. By integrating mechanized processes, mustard cultivation can achieve higher resource efficiency, minimize manual labor and improve the profitability and sustainability of the harvest.

Keywords: *mustard, mechanization, preharvest handling, postharvest handling*

INTRODUCTION

Mustard is a very versatile crop grown in different regions of the world and is known for its adaptability to different agroclimatic conditions and relatively high yields (Sharma et al., 2024). It thrives in temperate and subtropical climates and is mainly grown in countries such as India, Canada, Russia and the United States. Mustard plants tolerate a range of soil types and weather conditions, making it an important crop in various agricultural systems. Mustard belongs to the Brassicaceae family, which also includes crops such as cabbage, broccoli and rapeseed. Mustard seeds are produced for a variety of purposes. The oil extracted from the seeds is rich in unsaturated fatty acids, especially omega-3 and omega-6 fatty acids, which are important for human health. Mustard oil is also a staple in many culinary traditions, particularly in South Asian and Mediterranean cuisine, where it is prized for its strong, pungent flavor and high smoke point (Raghavan, 2006).

In addition, the mustard seeds are commonly ground to make mustard powder or mustard paste, a popular condiment worldwide. The seeds also contain several bioactive compounds, including glucosinolates, phenolic acids and flavonoids, which are thought to have antioxidant, anti-inflammatory and potentially anti-cancer properties. These compounds contribute to the health benefits of mustard, especially in traditional medicine (Grygier, 2023).

In addition to its culinary and nutritional uses, mustard is also an important forage crop, providing a valuable source of protein and energy. The meal remaining after oil extraction can be used as a protein-rich feed supplement for livestock and poultry.

In agriculture, mustard serves as an important rotation crop, often grown between other crops to break pest cycles, improve soil fertility and reduce the risk of soil erosion. Its deep root system can also help to break up compacted soil layers and improve soil structure (Shah et al., 2021).

Overall, mustard is a valuable crop that offers numerous benefits, including high oil yields, potential health benefits and environmental benefits, making it an important part of the agri-food industry (Hagos et al., 2020).

Mechanization has been instrumental in optimizing mustard production, making it more efficient and cost-effective, especially as the demand for higher yields and better seeds continues to increase. As mustard is grown in many countries, mechanization has become an integral part of the growing process, improving not only yield but also the overall quality of the crop and reducing labor costs.

PREHARVEST PROCESSES

Although it is grown worldwide, the main producing countries are Canada, Nepal, the USA, Russia, the Czech Republic, Romania, Slovakia, Germany, France and the United Kingdom. Mustard is generally a cool season crop that is well adapted to short growing seasons (Matin et al., 2024). According to Bharati et al., (2022) and Shekhawat et al., (2012), it can also be grown in tropical and subtropical regions as a cold-hardy plant that can tolerate annual precipitation between 500 and 4200 mm and temperatures between 6 and 27 °C. Mustard can grow up to 150 cm tall, the young shoots are hairy, the stems are erect, the edges can be serrated or whole, and it usually flowers from March to May and bears fruit from May to June. The vegetation period is short, lasting around 30 days from sowing to harvest. The optimum temperature range for mustard growth is between 12 °C and 25 °C, with the highest yield being obtained at a temperature of about 20 °C, while higher temperatures have a negative effect on the oil content (Jankowski et al., 2020).

The authors Bala et al., (2011) conducted a study to determine the optimum sowing time for mustard and analyzed the effects on seed and oil yield. Their results showed that the best yields were obtained when sowing between November 4 and 15, while later sowing significantly reduced yields due to unfavorable climatic conditions and a shortened growing season. The authors also note that some varieties have better resistance to late sowing and higher yields, while some varieties have a higher oil content. Uniform plant growth and adequate plant density are key to a successful harvest, while later sowing increases production costs due to additional investments in crop protection and irrigation. In addition, the use of mechanized sowing techniques has revolutionized the way mustard is planted. Modern seed drills and pneumatic planters allow for uniform seeding depth and planting density, which is essential for maximizing yields. Adequate plant spacing and uniform growth are essential for mustard crops, and machine seeding ensures this uniformity, which is difficult to achieve manually. The introduction of minimum tillage and no-till has further improved productivity. These methods help to conserve soil moisture, reduce erosion and promote root development, especially in regions where water availability can be a problem.

There are several varieties, the most important of which are yellow or white mustard, brown or oriental mustard and black mustard (Sharma et al., 2024).

Yellow or white mustard (Sinapis alba, syn. Brassica hirta Moench or Brassica alba) is native to southern Europe but is now mainly grown in Australia, China, Chile, Denmark, Italy, Japan, the United Kingdom, the Netherlands, North Africa, Canada and the USA (Farrell, 1985). It is an annual herbaceous plant that can grow up to 1.2 m tall. The plant produces bristly, ribbed pods containing round, yellowish seeds that mature in 80–85 days.

Black or dark brown mustard (*Brassica nigra*), also known as true mustard, is an annual herbaceous plant that can grow up to 3 m high. It forms small, light yellow, cross-shaped flowers with four petals. The fruit is smooth, square and has a short beak, while the seeds are about 2 mm or less in size, reddish-brown to black in color and ripen in 90–95 days.

One of the key elements is tillage and sowing technique. The optimal timing of mustard harvest is crucial for achieving maximum yields and oil quality. Although harvesting at full maturity gives a slightly higher oil yield, a longer harvest can lead to losses due to cracking and difficult mechanization (Talukder et al., 2020).

Minimum and no-till have been shown to be particularly suitable for maintaining soil moisture and thus creating better conditions for root growth and higher yields. Importantly, no-till concentrates nutrients in the top soil layer, which facilitates mechanical seeding and reduces the need for further tillage (Shekhawat et al., 2012). The authors note that seeding on raised beds allows for better water flow and increases yields, especially in high salinity conditions. On the other hand, by optimizing the harvest by timing the harvest so that the seeds fall optimally, losses during the process can be reduced.

The introduction of special mustard harvesters further improves efficiency and reduces seed damage. The application of integrated nutrient management systems significantly increases the efficiency of resource use, reduces nutrient losses and ensures consistent yields, which facilitates the mechanization of the harvesting process. In addition, precision farming methods such as adjusting nutrient levels and improving soil structure create optimal conditions for the use of mechanical machinery during harvest, reducing the risk of crop damage and increasing overall productivity.

Integrated nutrient management systems have been introduced to further improve the mechanization process. These systems help to optimize the use of fertilizers, water and other resources, reduce nutrient losses and ensure that the soil remains fertile and suitable for growing high-yielding mustard. Precision farming, including adjusting nutrient levels based on soil tests, helps increase soil fertility and crop yields. These practices ensure that crops grow in optimal conditions, further improving the efficiency of mechanical harvesting through uniform growth and reduced crop damage.

Proper application of potassium and sulfur during mustard cultivation not only significantly improves post-harvest soil quality, but also ensures stable conditions for the efficiency of mechanical harvesting methods and maintenance of productivity (Gajghane et al., 2015).

Harvesting itself is a key process in mustard production, as proper execution ensures that seed quality is maintained, and losses are reduced. Mustard is harvested when the majority of the pods (80-90 %) have turned golden yellow or brown. The seeds in the pods should be firm and fully ripe. The optimum humidity for harvesting is between 20 and 30 %, which prevents the pods from bursting and the seeds from being lost. In Europe, mustard seeds are always harvested by direct mixing or swathing, with the moisture content of the seeds being between 12 and 13% (Bañuelos et al., 2013).

Mechanized harvesting with combine harvesters has made this process much more efficient. However, the setting of the combine harvester is crucial in reducing seed damage. The speed of the drum and blower must be carefully calibrated to avoid breaking smaller seeds and causing excessive seed loss. The harvester uses fine sieves to retain even the smallest seeds, which is important as mustard seeds are relatively small and can easily be lost if not handled properly.

Harvesting can be done using direct or indirect methods. Direct harvesting with a combine harvester is faster but carries a higher risk of seed loss due to the pods bursting open. Indirect methods, such as row cutting, are slower but result in lower losses. With row cutting, the grain is cut and dried in the field before the seed is harvested from the swath with a combine harvester. This process allows the seed to dry evenly, reduces damage to the seed and reduces the risk of the pods bursting prematurely. Immediately after harvesting, the seed is transported to a drying or storage location.

By reducing the amount of manual work involved in sowing, irrigation and harvesting, mechanization helps to reduce production costs. In addition, better resource management, such as optimized irrigation systems and nutrient management, further improves overall productivity. Mechanization also contributes to more consistent yields, allowing farmers to predict crop yields more accurately. This predictability helps to meet market demand and ensure food security.

POSTHARVEST PROCESSES

Mechanization plays an important role in the drying and storage of mustard seeds, as it increases efficiency and ensures the preservation of quality and nutritional value. After harvest, mustard seeds often have a high moisture content, which can make direct storage problematic, as excess moisture can lead to mold growth, spoilage and loss of quality. Therefore, drying is a crucial step before storing mustard seeds for long periods of time. This process can be achieved through various mechanical and thermal methods, each tailored to optimize the efficiency and preservation of the seeds.

Drying is widely used in the food industry to remove moisture from cereals, vegetables and fruit (Matin et al., 2023). Drying mustard seeds is essential to reduce their moisture content to a safe level (below 8%) so that they do not spoil during storage. The two main methods for drying mustard seeds are conduction drying and convection drying.

Conduction drying is the drying of raw materials by direct contact with a heat exchanger, e.g. a heated surface or drum, through which the temperature is transferred to the raw materials. This method is well suited for drying small quantities of seed and is particularly useful when a fast, localized drying method is required. Conduction drying is often used on smaller farms where precise temperature control is required.

Convection drying is the most common method for drying large quantities of mustard seeds. In convection drying, heated air is blown over or through the seeds, causing the moisture to evaporate. As the air flows over the seeds, it absorbs moisture, which is then transported away. This method is more efficient when drying larger quantities of mustard seeds and is therefore the preferred option for commercial and industrial operations. Convection dryers, such as batch dryers or continuous dryers, can handle large quantities of material and can be adjusted to achieve uniform results (Kannan and Kramer, 1994).

Both methods require careful temperature control to maintain the nutritional quality of the seeds and avoid damage. Research has shown that the temperature range for drying mustard seeds should be between 50 and 75 °C (Van Eylen et al., 2006). Higher temperatures can affect the nutrient content of the seeds, so it is important to use the lowest possible temperature that still ensures effective moisture removal. Thermal drying systems, whether conductive or convective, are optimized to maintain this temperature range while achieving the moisture reduction required for safe storage.

After drying, the mustard seeds must be stored for longer or shorter periods, depending on how they are processed. For longer storage, particular attention should be paid to the microclimatic conditions in the warehouse. The storage temperature influences the post-harvest quality and the behavior of the fresh product (Matin et al., 2022; Matin et al., 2024). The optimal storage temperature depends mainly on the type of product and is important for maintaining freshness, nutritional quality and consumer acceptance. Mustard seeds can be stored for a long time if their moisture content is below 8 % and the storage temperature is less than 25 °C (Dayarathna et al., 2023; Xiao et al., 2016). Lowering the storage temperature by 10 °C can slow down the metabolic activity of enzymes (Trierweiler and Weinert, 2019), which means that storage at low temperatures reduces quality loss and extends shelf life by reducing the respiration rate, tissue aging and the activity of microorganisms that can cause product spoilage. However, excessively low temperatures can cause chilling damage to and within produce during post-harvest or post-harvest storage (Rai et al., 2020).

The ideal temperature for mustard seed storage is below 25 °C, as higher temperatures can accelerate seed decay. Storage at a lower temperature, especially at 10-15 °C, has been shown to slow down metabolic processes, reduce the respiration rate of seeds and minimize microbial activity (Sun et al., 2020). Maintaining a cooler environment extends the shelf life of the seed and preserves its quality for longer.

In addition to temperature, controlling the relative humidity in the storage rooms is also crucial. Mustard seeds should be stored in environments where humidity is kept low to prevent the reabsorption of moisture. Excess moisture can lead to mold growth, which spoils the seed and makes it unsuitable for further use or processing (Ashworth, 2002).

The integration of mechanical systems into storage facilities has made it easier to monitor and control microclimatic conditions in warehouses. Automated storage systems equipped with sensors and climate control technology allow for continuous monitoring of temperature and humidity in real time. These systems can adjust the environment within the warehouse to maintain the ideal conditions for the preservation of mustard seed.

In addition, ventilation systems and air circulation within the storage units are crucial to ensure that air flows evenly and moisture does not accumulate. Mechanized systems such as air conditioning and humidifiers (or dehumidifiers) work together to stabilize the storage environment and create optimal conditions.

Although lower temperatures can effectively slow down the metabolic processes of the seeds, storing mustard seeds at very low temperatures also poses problems. Exposing seeds to low temperatures can cause chilling damage, which damages the internal structure of the seed. This can reduce the germination rate, and the seeds may not thrive when sown in the next planting season.

As Turner et al., (2020) found, excessively low temperatures can damage both the seeds and the tissue inside them. Therefore, while cold storage is beneficial for maintaining seed quality, it is important to maintain an optimal temperature range to avoid cold damage. This highlights the importance of temperature regulation and the role of mechanized cooling systems in ensuring that mustard seeds are stored at safe, effective temperatures.

The mechanization of mustard drying and storage is a crucial aspect of modern agriculture, ensuring that harvested seeds are processed and stored effectively. By using mechanical drying systems such as conduction and convection dryers and implementing temperature and humidity control systems in storage facilities, farmers can significantly extend the shelf life of mustard seeds and maintain their quality over a longer period of time. Proper post-harvest handling using mechanical equipment such as grain separators and seed cleaners ensures that mustard seeds meet high-quality standards, contributing to both higher yields and better product consistency on the market. As technology continues to develop, the mechanization of mustard processing and storage is likely to play an even greater role in improving agricultural productivity and sustainability.

CONCLUSION

The mechanization of mustard cultivation plays a decisive role in improving productivity and reducing labor-intensive processes. Automated sowing techniques, precision cultivation methods and the use of specialized mustard harvesting machinery are essential to maximize yield and minimize losses during the cultivation and harvesting stages. Mechanized post-harvest processes, including drying and storage, further increase efficiency by ensuring consistent seed quality and extending shelf life. By taking advantage of technological advances in mechanization, mustard farmers can reduce operating costs, improve crop management and ensure better resource utilization, ultimately leading to greater profitability and sustainability in mustard production. As mechanization continues to evolve, its integration into mustard production will continue to be critical to meet the growing global demand for this versatile crop.

By reducing the amount of manual labor involved in sowing, irrigation and harvesting, mechanization helps to lower production costs. In addition, better resource management, such as optimized irrigation systems and nutrient management, further improves overall productivity. Mechanization also contributes to more consistent yields and allows farmers to predict crop yields more accurately. This predictability helps to meet market demand and ensure food security.

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50. ACTUAL TASKS ON AGRICULTURAL ENGINEERING

Original scientific paper

A NEW DEVICE FOR TRANSPORTING AND OPERATING LARGE AND MEDIUM REVERSIBLE PLOUGHS

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ABSTRACT

The paper details the design of an innovative device for the transportation and operation of medium and large reversible ploughs, with an emphasis on its adaptability to various models of agricultural ploughs, which are still the main implements used in soil tillage. The device allows easy adjustment of the working depth, full turning of the tractor during transportation and reversing of the ploughs without mechanical shocks. It is also designed to fit within the working width of the plough, ensuring safe and efficient operation.

The design began in response to the challenges posed by the heavy weight of ploughs on rough farm roads, where unevenness caused sway, material fatigue and, in some cases, breakage of the tractor's side tie-arm arms. In the absence of a semi-weight-bearing system, the entire weight of the ploughs was carried by the tractor, leading to premature wear. The designed device distributes the weight evenly and prevents damage to both the plough and the tractor.

The 3D design steps, realized in Catia V5, were followed by static simulations in Fusion360, which validated the strength of the device under real working conditions. Finally, an efficient method for the physical realization of the device is proposed to improve the transportation and adjustment of medium and large size reversible ploughs. This solution demonstrates viability and practical implementability, bringing significant improvements in the use of agricultural ploughs.

Keywords: *ploughs, FEA, static simulation, soil tillage*

INTRODUCTION

Agriculture plays a key role in the global economy, facing challenges such as food security, population growth and climate change. These put pressure on natural resources and the environment. Continuous innovation and precision farming, using modern machinery and advanced techniques, are key solutions to these problems (Bulgakov et al., 2022). The main reason for this work is related to medium and large reversible agricultural ploughs with 4-7 tines. These machines are long, robust and heavy, due to the space required between the working parts for tillage and the solid components exposed to high loads and wear (Sun et al., 2023). Their weight is carried by the tractor's drawbars over short distances, but over long distances a significant part of it is taken by a transport wheel (Zhu et al., 2016). Due to the length of the plough, the center of gravity shifts considerably behind the tractor's axle, causing vibration and rocking on uneven ground or even flat surfaces, especially during acceleration and braking (Bulgakov et al., 2022). This can become dangerous in many situations and in others it can even lead to shocks that can break/destroy tractor hitch components or cracks in the reversing bolt of the plough that over time will lead to the plough breaking.

The correct choice of the right plough can significantly influence the efficiency, quality and productivity of agricultural operations, which is why companies producing this type of machinery are in constant competition to invent, technologize and achieve the highest possible performance of these machines (Singh, 2017; Lee and Nam, 2019;).

Thus, a number of problems were identified, concerning the way of working and transportation over longer distances, in a wide range of ploughs from different manufacturers (Beket et al., 2020; Singh, 2017) turning angle in the transport position was limited, the model H_475E, manufacturer Huard, was found to be out of the working width of the plough, the reversing of the wheels was done with a shock, the working depth was rather difficult to adjust, (Anzhe et al., 2024) Rover 50, Gregoire Besson and Juwel 6, Lemken, not within the working width of the plough, hydraulic reversing necessary, Master 153, Kuhn, use of an additional wheel for transporting the machine, the working depth adjustment dimensions are much more limited, XS 950, Amazone, not within the working width of the plough, limited turning angle in transport position. (Yin et al., 2018; Balwani et al., 2016).

All this shows the need for an innovative device to take the weight of the plough during long-distance transport to prevent distortion of the machine and the tractor, and to make tractor acceleration and braking more efficient, especially on public roads. This system must also serve the purpose of allowing the device to be used during operation without compromising the stability and optimum operation of the tractor.

MATERIALS AND METHODS

To create the most efficient and practical device, we have set out some essential requirements that it must fulfill. First, the working depth must be easily adjustable. At the same time, the device must allow the plough to be transported both in the tractor's tie rods and, on the wheel, used for adjusting the depth. It is also important that, in the transport position, the tractor can turn at full capacity. The dimensions of the device must be compatible with the working width of the plough and the reversing process must be carried out without shocks in the system. Finally, the device shall be easily adaptable for a variety of plough designs.

This device has been designed for the Huard H_475 E plough with a number of 5+1 tines, reversible plough with a total mass of 1600 kg, beam height from the ground of 800 mm and beam profile of 140x140 mm, and the angle of positioning of the beams in relation to the central body can vary between 28 degrees when the plough is set to the minimum working width and 46 degrees when the plough is set to the maximum working width.

Design of the device

For the design of the device, we devised a clamping system for the plough beam so that it is easily adaptable to different plough models. We developed a reversing mechanism that operates without shocks, ensuring a direct correlation between the reversing speed of the wheel and the plough. We also designed a quick-acting system that allows easy switching between transport and working position. We also sized the wheel support fork, which is an integral part of the device's adjustment system and calculated the dimensions of the holes and bolts required for assembly. The software used to design this device was CATIA V5 (Strietzel, 2015). The device for supporting the plough during transportation as well as for working under load consists of several sub-assemblies and essential components, as can be seen in figure 1.a), b), c), d). It includes the elements of the figure 1 a) device, the working depth adjusting anchor illustrated in figure 1 b), the transport wheel assembly shown in figure 1 c), and the locking and unlocking system between the working and transport position, which is illustrated in figure 1 d). All fastenings shall have hardness class 10.9 to withstand the stresses to which the transportation and working device is subjected.

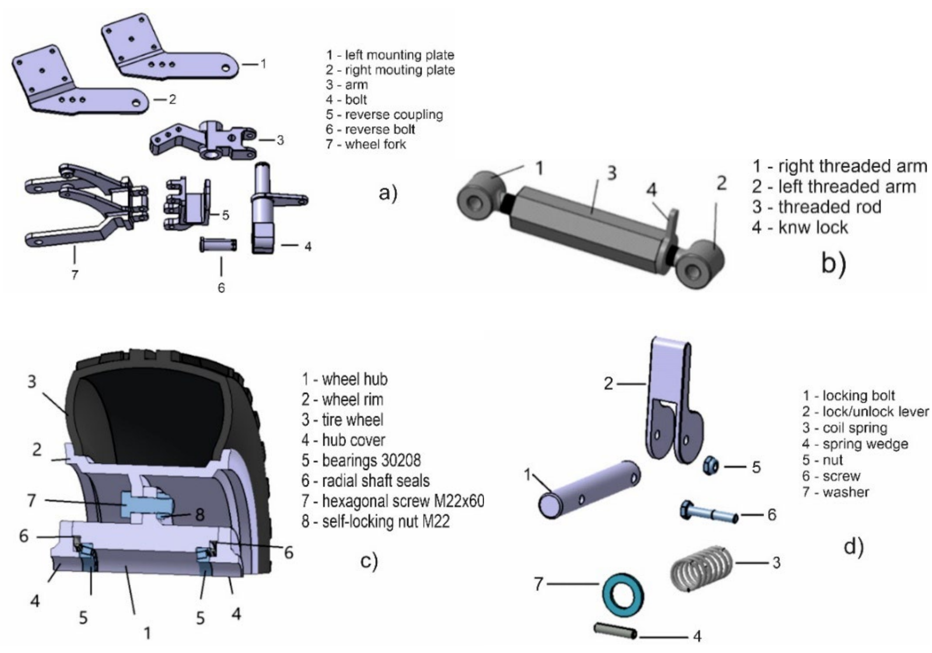

Figure 1. Components of the device: 1a) elements; 1b) anchor; 1c) transport wheel assembly; 1d) the locking and unlocking system;

In figure 1 c), it can be seen that there is no friction between the parts of the wheel assembly, more precisely between the hub and the hub caps, due to the fact that the axial stresses caused by the tightening of the wheel fixing bolt are taken up by the radial-axial bearings and that there is a space of about 2 mm between the hub and the caps, especially designed for this purpose. To prevent dust and impurities from entering the bearings, an oil seal was fitted on each side of the wheel hub.

Figure 2a) shows an isometric view of the complete assembly in the transport position unattached to the plough and Figure 2b) an isometric view of the complete assembly in the transport position attached to the 5+1-row plough.

The bar supporting the plough on the tractor's side drawbars shall be at 1050 mm from the ground, which is 95 % of the lifting height of the tractor's drawbars. The plough is positioned at three points, namely on the wheel and on the two ends of the bar, where the tractor's side tie rods are arranged.

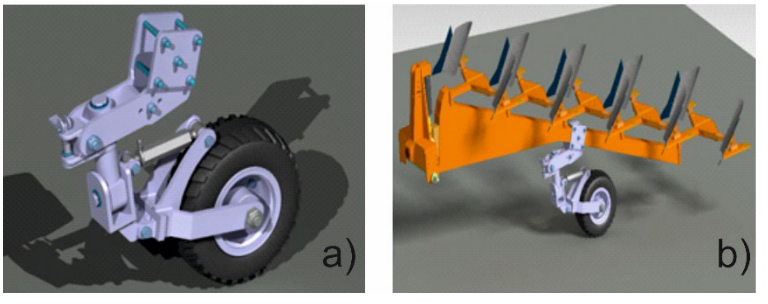

Figure 2. Isometric view of the complete assembly in transport position: a) not attached to the plough; b) attached to the plough

Figure 3a) shows the isometric view of the device assembly arranged in the working position unattached to the plough and Figure 3b) shows the isometric view of the device assembly in the working position attached to the plough. The wheel acts as a level sensor which determines the working depth of the plough. It shows the fit of the device within the working width of the plough, noting that the wheel fits within the working space of the plough body.

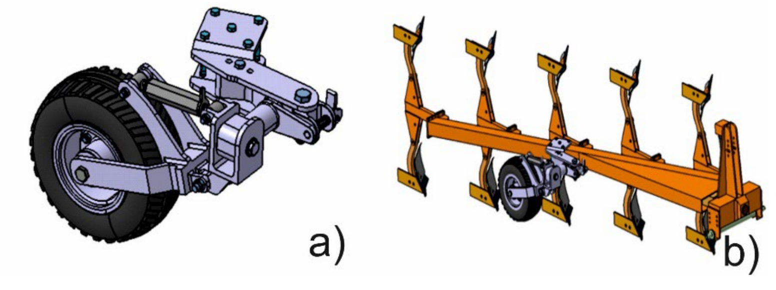

Figure 3. Isometric view of the complete assembly in working position: a) not attached to the plough; b) attached to the plough

Finite element analysis of the device

The objectives of static simulations include the determination of the stress distribution in the modeled structure to identify critical points where stresses could exceed the material limits. It also aims to evaluate the deformations of the structure when subjected to loads to verify that they remain within acceptable limits. In addition, the simulations are intended to calculate the factor of safety, ensuring that the structure can withstand the applied loads without the risk of failure. The software used to simulate this device was Fusion 360 (Okereke and Keates, 2018; Vladut et al., 2018; Ochsner and Altenbach, 2023).

For the static test, a discretization was used with dimensions of 2% of the configuration of the parts in simple triangular geometries, this resulted 132864 nodes and 78346 elements for the device in the transport position Figure 4a); and the discretization for the working position of the device resulted 137192 nodes and 80976 elements Figure 4b). In the analysis only sliding contacts were used for both the transport and working position of the device, to see the maximum load reaction on each part.

For the transportation position, pin-type constraints were used with radial and axial locking in the two holes of the forks where the wheel axle is fixed, and fixed-type activated on the x and y axes and free on the z axis, to allow vertical movement of the device. The load used was a force-type load with a magnitude of 16000 N representing the full mass of the plough, arranged in the 10 holes of the plates fixing the device to the plough beam and arranged on the z-axis, Figure 4a). This figure shows the discretization, the forces and constraints imposed on the device in the transport position, as well as its positioning with respect to the symmetrical axes which are distinguished by color as follows: blue z-axis, green y-axis and red x-axis.

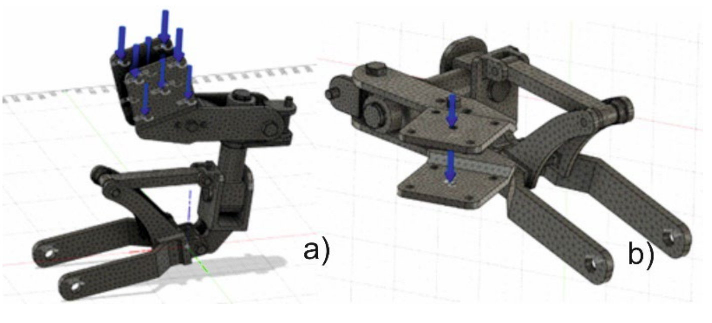

Figure 4. The discretization, forces and constraints on the device: a) in the transport position; b) in the working position

For the working position, pin-type constraints were used, with radial and axial locking in the two fork holes where the wheel axle is fixed, and fixed-type activated on the x and z axes this time and free on the y axis due to the change of the position of the fixing plates with regard to the axes of the coordinate system, to allow vertical displacement with respect to the ground. The same load has been placed on the surfaces of the mounting plates where the plough beam is in contact with them, to simulate the force acting on the device given by the full weight of the plough. Figure 4b) shows the discretization, the forces and constraints imposed on the device in the working position, and its positioning with respect to the symmetrical axes which are distinguished by color as follows: blue z-axis, green y-axis and red x-axis. In the two static simulations, C45 (OLC 45) steel was used for the device parts. 34CrNiMo6 steel was used for the screw and bolts and their properties are shown in Table 1.

Table 1. Materials used and their properties in static simulations

Component	Material	Young's module (E)	Poisson coefficient (ν)	Ultimate strenght (σ_c)	Tensile strength (σ_r)
Device components	Steel (C45)	207,00 GPa	0,33	516,00 MPa	751,00 MPa
Screw and bolts	Steel 34CrNiMo6	207,00 GPa	0,33	1102,00 MPa	1171,00 MPa

RESULTS AND DISCUSSION

The test results indicate that both the assembly and the chosen screws successfully resisted the loads to which it is exposed, the maximum loads on the device occur on the screws at the ends of the working depth adjustment anchor, as was also intended.

The following figures show the results obtained from the simulations for the device in the transportation position and in the loaded working position. In the first test, an area was detected that had a much too low safety factor that could lead to deformation or even cracking over time or aftershocks. The safety factor in Fusion 360 is to validate the strength of the part or assembly is required to be a minimum of 3, Figure 5.

The minimum safety factor in the working depth adjustment anchor bolt is also shown. Figure 6 shows the area where the safety factor is minimum and which in this case validates the strength of the structure by increasing the weld section. Figure 7 shows stress distribution after running the finite element analysis program. It can be seen that the maximum stress is in the bolt area of the rolling wheel attachment fork. Figure 8 shows the distribution of displacements. The maximum deformation is $\delta_{max} = 1{,}852\ mm$ and occurs on the plates gripping the plough beam. The deformations of the device with respect to the initial unstressed position (in the drawing it is represented by marking its contour) are very small after applying the stresses.

The above analyzed case is realized for the transportation situation of the device. Figure 9 shows the point where the pressure is maximum for the whole assembly. Figure 10 shows the maximum stress (maximum pressure) occurring on the bolt designed to fail in the event of an unforeseen (extremely large and rapid) shock.

Figure 11 shows the maximum force exerted on the bolt in static mode. The maximum force has the value $F_{max} = 8519{,}363\ N$ c that also occurs on the bolt designed to fail first. Figure 12 shows the values of the safety factor in case of deformation of the assembly in the working position. The working position stresses on the device are shown in Figure 13.

Transportation position

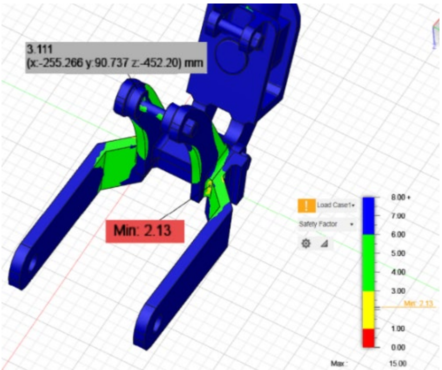

Figure 5. Insufficient safety factor

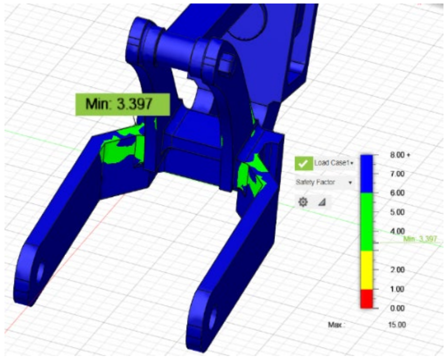

Figure 6. Area where the safety factor is minimal but valid

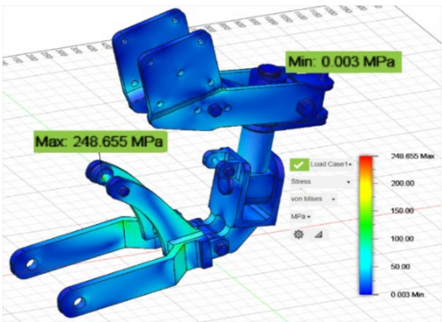

Figure 7. Device stress distribution

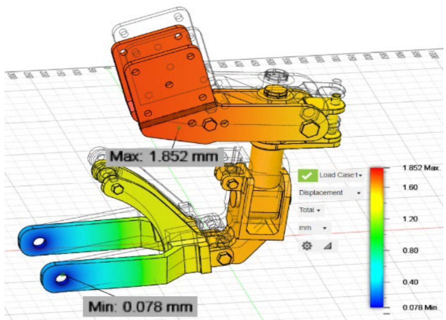

Figure 8. Maximum and minimum deformation

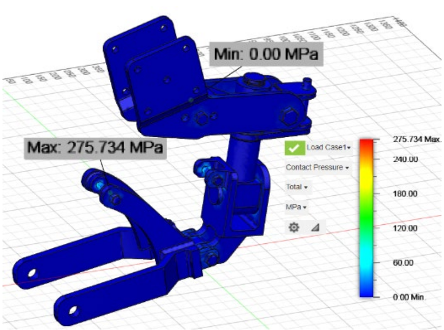

Figure 9. Maximum device pressure

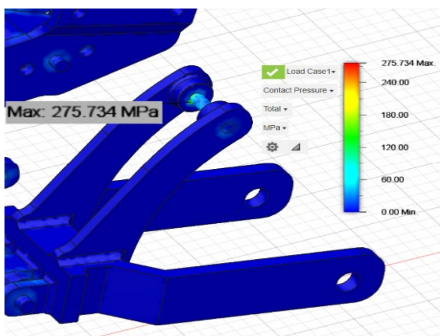

Figure 10. Maximum bolt pressure

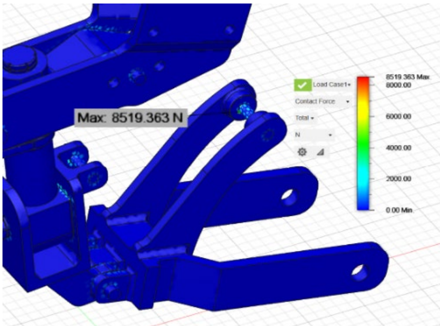

Figure 11. Contact point with maximum force

Working position

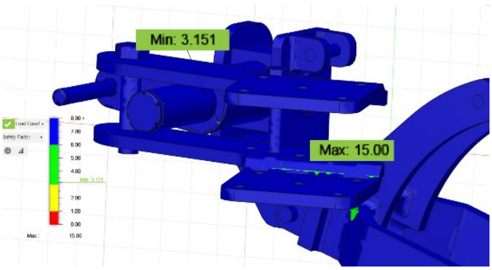

Figure 12. Safety factor in working position

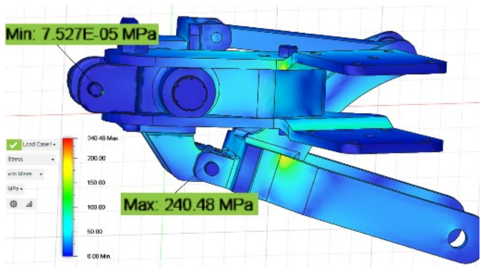

Figure 13. Device stress distribution

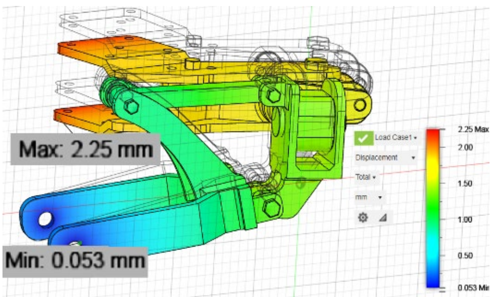

Figure 14. Maximum and minimum deformation of the device

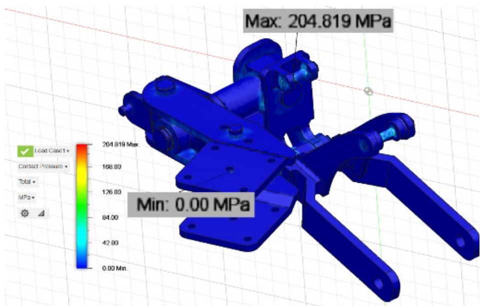

Figure 15. Device contact pressure

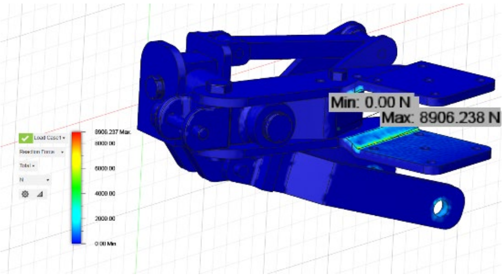

Figure 16. Device maximum force

It can be seen from the stress analysis that the maximum value of the stress does not exceed the material yield strength:

$$\sigma_{max} = 240{,}48\ MPa < \sigma_c = 516\ MPa \quad (1)$$

Figure 14 shows the deformations (minimum and maximum) occurring in the device in the working position. Very small deformations (2.25 mm) can be observed, which give us confidence that the device provides sufficient resistance against the loads to which it is subjected.

The image shows the displacement of the device with an exaggeration of 25 times the actual deformation of the device with comparison to its initial position (marked by the gray outline of the device), in order to observe the deformation mode.

Figure 15 shows the contact pressure occurring in the most stressed screw of the device. The maximum value of the contact pressure is $\sigma_{max} = 204{,}82\ MPa$ on the screw, which indicates that it is the most stressed part in the device, being the first part susceptible to failure. Figure 16 gives the maximum force occurring in the device in the working position. It can be seen that the maximum force is $F_{max} = 8906{,}238\ N$, acts on the lower and upper clamping plates of the plough beam.

Knowing the maximum force acting on the plough clamp, analytical checks can be made on the lower and upper plates. The dangerous section of the plate has dimensions of 20x240 mm2.

The cross-sectional area of the plate is calculated with the relation:

$$A = t \cdot l \quad (2)$$

where:

t - is the plate thickness, l - is the plate width.

The maximum stress accumulated in the plate will be:

$$\sigma = \frac{F}{A} = \frac{F}{t \cdot l} = \frac{8906{,}237}{20 \cdot 240} = 1{,}86\ MPa \quad (3)$$

It can be observed that very little stress is obtained acting on the plates in the most stressed position (working under load position).

This result confirms that the maximum stress in the device occurs on the bolts of the working depth adjusting tie-rod, parts that are easy to change having also the lowest material and labor costs.

CONCLUSIONS

The conclusions that can be drawn from the analyzed material highlight that the design of the device for the Huard H_475 E plough aimed at meeting essential criteria such as ease of working depth adjustment, adaptability to various plough models and a shock-free reversing mechanism. Through tests and simulations, it was confirmed that the device provides adequate performance in both transport and working positions and that critical elements such as bolts and fastening plates provide sufficient resistance to the applied loads. The finite element analysis revealed that the stresses and deformations of the structure remain within acceptable limits, validating the reliability of the device in use. The greatest stress occurs on the working depth adjusting tie bolts, but these are easily replaceable and relatively inexpensive components.

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50. ACTUAL TASKS ON AGRICULTURAL ENGINEERING

Preliminary communication

RAPESEED PRODUCTION IN TWIN ROW TECHNOLOGY IN THE REPUBLIC OF CROATIA

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ABSTRACT

The paper presents the results of sowing the hybrid rapeseed KWS Granos at the Tenja experimental field (N 45°29'55.0032'' E 18°48'16.9092'') of the Faculty of Agrobiotechnical Sciences in Osijek. The sowing of rapeseed using twin row technology was carried out in 20 different plant densities per hectare. The paired rows were sown at an interval of 22 cm, and the central distance between adjacent paired rows was 70 cm. The smallest established density at harvest time was 185 121 plants per hectare, and the largest was 686 520 plants per hectare. The highest grain yield was recorded at a plant density of 296 875 per hectare, amounting to 5993 kg per hectare. A high grain yield of 5 982 kg per hectare was also recorded at a density of 289 876 plants per hectare. Similarly, the group of densities from 185 121 to 275 389 plants per hectare achieved yields over 5 300 kg of grain per hectare. The lowest recorded yield in the experiment was at a density of 686 520 plants per hectare, or 68.6 plants per square meter, amounting to 4 861 kg per hectare with a grain moisture content of 8.9 %. The highest oil content in dry matter of 50.58 % was found in plant densities ranging from 52.3 to 68.6 plants per square meter. The lowest oil content in dry matter of 47.72 % was recorded in the highest yielding plant densities, ranging from 27.9 to 32.7 plants per square meter. The highest hectoliter weight was found in the group of plant densities per hectare ranging from 235 897 to 250 521 and amounted to 66.36 kg. In standard sowing with a row spacing of 70 cm and a density of 461 234 plants per hectare, the highest grain yield of the KWS Granos hybrid was achieved at 5 469 kg per hectare. The lowest grain yield in sowing with a row spacing of 70 cm was achieved at a density of 42.6 plants per square meter.

Key words: *rapeseed, twin row, KWS Granos, yield, plant density*

INTRODUCTION

Rapeseed, (*Brassica napus* var. *napus*), is a winter or spring annual oil crop in the Brassica family. It is also known as rape and oilseed rape. Rapeseed is related to mustard, cabbage, broccoli, cauliflower and turnip. Rapeseed plants grow from three to five feet tall and have yellow flowers with four petals. It has a deep taproot and a fibrous, near-surface root system AgMRC (2022). At the global production level, oilseeds are the fourth most essential food products, behind cereals, vegetables, and fruits, occupying 213 million hectares (ha) of arable land, according to the OECD-FAO report (2022). Rapeseed (*Brassica napus*) is the third most important oilseed in the world. Rapeseed is primarily grown for oil, but it is also used in the food and manufacturing industries. Rapeseed is an annual plant and thrives very well in relatively wetter and cooler climatic areas. However, it should be noted that oilseed rape does not tolerate very water-saturated soil, and the crop quickly deteriorates under such conditions. Newer rapeseed cultivars, due to their high yields and oil content of over 45%, are suitable as raw materials for biodiesel production, according to Tanner (2023). From the grain produced per hectare, up to two tons of oil can be obtained, making it the highest-yielding oilseed crop. Additionally, the resulting biodiesel has a low gel point, which is the temperature at which diesel will no longer flow through fuel lines (Rapier, 2008). Villanueva-Mejia (2017) states that due to population growth, dietary diversity, and the need for bio-products, the production and demand for oilseeds have been continuously increasing over the years. The production of rapeseed worldwide increased by about 3.3 times between 1994 and 2018, while the arable land area almost doubled, according to Iriarte (2010).

In 2022, Europe had rapeseed production on 10 168 328 hectares with a total production of 29 688 677.05 tons, representing 34 % of the world's production (87 221 220.62 tons). The largest European producers of rapeseed in 2022 were Germany with 4 294 900 tons, France with 4 516 540 tons, and Poland with 3 487 070 tons. These three countries alone produced 41.42 % of Europe's rapeseed production (FAOStat, 2024). Rapeseed provides good soil cover during winter and prevents soil erosion, produces large amounts of biomass, inhibits and reduces weed growth, and contributes to easier soil cultivation with its root system, according to AgMRC (2022). Rapeseed could achieve similar seed yields over a wide range of plant densities per square meter, as noted by Roques et al. (2016) and Seepaul et al. (2016), offering the possibility to reduce the seeding rate per hectare. However, although rapeseed can adapt well to climate change, agroecological and weather conditions can significantly affect its productivity, like to other crops. Climate change impacts global agricultural production in various ways, including differences in annual rainfall, average temperature, CO_2 emissions, etc., as stated in the EEA reports (2019) and EEA (2020). To meet the projections of the Food and Agriculture Organization (FAO) for food, fuel, and industrial demand, global vegetable oil production is expected to double by 2050, according to the FAO report (2017).

MATERIALS AND METHODS

Rapeseed production in the Republic of Croatia

In 2020, rapeseed was sown on 41 661 hectares according to data from the Croatian Bureau of Statistics (CBS). In 2020, an average yield of 2.9 t ha^{-1} was achieved across Croatia, with a total production of 119 667 tons. In 2021, the harvested area was 30 261 hectares, which is 27.36 % less compared to the previous year's production. That year, an average grain yield of

2.4 t ha^{-1} was achieved. The total grain production amounted to 73 423 tons. The main reasons for the decreased interest of producers in sowing rapeseed are primarily the ban on the use of certain insecticides and the appearance of larger pest populations, the occurrence of low temperatures during March and the beginning of flowering, which leads to significant plant damage and reduced grain yield, and very dry soil during the preparation and sowing of rapeseed. The reduction in sown areas from 7 861 ha continued in 2022 (22 400 ha), with an average yield of 2.6 t and a total national production of only 58 070 t of grain. The lowest recorded production of rapeseed was achieved in 2023, with only 15 210 ha, resulting in an average yield of 2.8 t ha^{-1} and a total production in Croatia of 43 049 t of grain.

Table 1. Spacing of plants in a row (cm) with different methods of sowing oilseed rape

Sowing methods	Row spacing (70 cm)	Row spacing (50 cm)	Row spacing (25 cm)	Twin row sowing (22x48 cm)
Rows per hectare	142	199	399	284
Plant density (ha^{-1})	Spacing of plants within a row (cm)			
200 000	7.10	9.95	19.95	14.20
300 000	4.73	6.63	13.30	9.47
400 000	3.55	4.98	9.98	7.10
500 000	2.84	3.98	7.98	5.68
600 000	2.37	3.32	6.65	4.73
700 000	2.03	2.84	5.70	4.06

Climatic conditions of rapeseed production at the experimental site Klisa

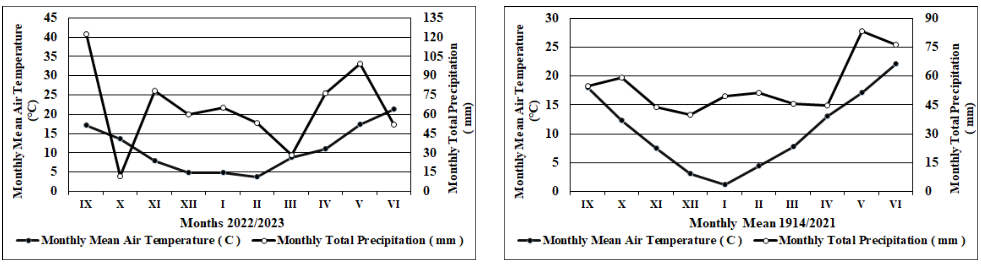
For optimal growth and development, rapeseed, like other plants, benefits from a few meteorological factors, especially soil moisture and temperature. Table 2 shows the average monthly air temperatures and total monthly precipitation (mm) for the 2022 and 2023 growing seasons. The values were measured at the main meteorological station Osijek - airport, which is closest to the faculty's experimental field and the trial location.

In September 2022, during the sowing period (September 23rd), the average monthly temperature was 17° C, which is 1.0° C lower than the long-term average. The trend of slightly higher average monthly temperatures continued through October, November, December, and January. In October, the average monthly temperature was 13.6° C, which is 1.3° C higher than the average of 12.3° C. The average monthly temperature in November differs very little from the long-term average. In December, a higher average monthly temperature of +1.7 °C was recorded. During January 2023, the average monthly temperature was 4.7° C, which is +3.5° C higher than the long-term average. After 4 months of plant growth and development at slightly higher average monthly temperatures, a decrease in the average monthly temperature of -0.6° C was recorded in February compared to the long-term average. In March, a higher average monthly temperature of +1.0° C was recorded again compared to the long-term average.

Table 2. Mean air temperature (°C) and total monthly precipitation (mm) - meteorological station Osijek – airport (45°28'4"N 18°48'23"E)

Month / Year	Air temperature (°C)		Precipitation (mm)	
	2022./2023.	2014.-2021.	2022./2023.	2014.-2021.
IX. / 2022.	17.00	18.00	122.30	54.60
X. / 2022.	13.60	12.30	12.00	59.00
XI. /2022.	7.90	7.50	78.00	43.70
XII. / 2022.	4.70	3.00	59.80	39.70
I. / 2023.	4.70	1.20	65.30	49.70
II. / 2023.	3.80	4.40	53.50	51.10
III. / 2023.	8.80	7.80	27.90	45.70
IV. / 2023.	10.90	13.00	76.00	44.50
V. / 2023.	17.30	17.10	99.20	83.40
VI. / 2023.	21.30	22.10	51.80	76.50
Total precipitation (IX-VI) (mm)	-	-	645.80	547.90
Mean air temperature (IX-VI) (°C)	11.00	10.64	-	-

Source: DHMZ (State Hydrometeorological Institute 2024.)



Source: DHMZ (State Hydrometeorological Institute, 2024)

Graph 1. Climate diagrams according to Walther method for period 2022/2023 (left) and 2014/2021(right) - meteorological station Osijek – airport (45°28'4"N 18°48'23"E)

During the month of April, the average daily temperatures were somewhat lower, leading to a decrease in the average monthly temperature by -2.1° C compared to the long-term average. The average monthly temperature in April was 10.9° C. In May, the average monthly temperature was negligibly higher than the long-term average by +0.2° C. In the last month of the 2023 rapeseed growing season, a slightly lower average monthly temperature of -0.8° C was observed, which positively affected the grain filling and overall ripening process of the rapeseed. The start of rapeseed sowing was influenced by the amount of precipitation, which amounted to 90.2 mm from September 1st to 23rd. The sowing of rapeseed was delayed beyond the optimal dates, and by the end of the month, an additional 32.1 mm of precipitation was recorded. The total monthly precipitation in September 2022 was 122.3 mm, which is 67.7 mm above the long-term average. The total precipitation from October to December was 149.8 mm, which is slightly above the long-term average. Additionally, the total recorded precipitation from January to June was 373.7 mm, while the long-term average for that period was 350.9 mm. During the 2022/2023 growing season for rapeseed production, a total of 645.80 mm of precipitation was recorded, which is 97.9 mm above the long-term average. In the same period, the average temperature of the total average monthly temperatures was higher by +0.36° C.

Sowing experimental field Tenja

To achieve the highest grain yield, oilseed rape should develop 8 to 12 true leaves, with a stem axis thickness of up to 2 cm, a branched root with a terminal diameter of 6 to 8 mm, and a length of over 20 cm before the onset of lower temperatures during December/January. In the region of Eastern Croatia, sowing oilseed rape in the first decade of September provides a sufficient period for the necessary development of plants before the appearance of low temperatures. In recent years, with the appearance of higher temperatures, sowing can be postponed until the end of the second decade of September. The most favorable sowing time also depends on soil conditions (soil moisture) in specific areas. Earlier sowing dates favor better and stronger plant development, increasing the possibility of greater frost damage, but also significantly greater insect damage. On the other hand, sowing at the end of September can affect the weaker development of plants that may be damaged by low temperatures. Rapeseed was sown on September 23, 2022, in a fine crumbly soil structure on a hard and moist bed at a depth of 2 to 3 cm at the experimental field of the Faculty of Agrobiotechnical Sciences Osijek – ‘Tenja’(N 45°29'55.0032" E 18°48'16.9092") located near the city of Osijek. For sowing in twin rows, the MaterMacc Twin Row-2 seeder was used with a twin row spacing of 22 cm. The seeder’s settings for the intended sowing are shown in Table 2.

Table 3. Technical factors during measurements

	Plant density (ha^{-1})					
Hole numbers of seed plate (n)	729,284	596,687	507,184	397,791	298,343	227,309
	72	72	72	72	60	48
Drive wheel to seed plate ratio (*i*)	0.5884	0.4814	0.4092	0.3209	0.2888	0.2751
Rotational speed (m s^{-1})	0.249	0.204	0.173	0.136	0.102	0.078
Spacing of plants within a row (cm)	3,894	4.760	5.600	7.139	9.519	12.494
Seed releasing frequency (s^{-1})	17.913	14.654	12.456	9.771	6.106	3.722

Dynamic drive wheel radius D_d=52.52 cm; Seed plate diameter=0.1979 m and hole ø 2. mm ; working speed 1.11m s^{-1}

With the MaterMacc Twin Row-2 seeder, using a PTO speed of 540 rpm, a vacuum of 47.13 mbar was achieved. For standard row sowing, with a row spacing of 70 cm, the Kuhn mono-grain seed drill Maxima 3 was used. Sowing with the Maxima 3 seeder was carried out at a PTO speed of 540 rpm, i.e., at 4 200 rpm of the fan shaft. In this way, with the seed plate filled (n=70), a vacuum of 45.80 mbar was achieved at the seed openings (ø 1.25 mm) of the plate.

Rapeseed hybrid KWS Granos

The hybrid rapeseed from the company KWS, named "KWS Granos", according to KWS (2024), is classified among hybrids with high potential for grain and oil yield. Due to its adaptability and moderate growth and development of plants before the onset of low temperatures, it is suitable for early and mid-sowing periods. The hybrid tolerates low temperatures well in the Eastern Slavonia region due to the favorable development of a very strong and branched root system. Such a root system ensures the uptake of necessary elements during the growing season and ensures an early to mid-flowering start. The hybrid KWS Granos possesses a high level of tolerance to lodging and the occurrence of a greater number of diseases in the production of rapeseed. The flower of this hybrid has a very rich floral rosette with uniform flowering, and thus uniform medium-early ripening of the pods. One of the significant genetic traits of this hybrid is its high tolerance to pod shattering during harvest. The grain yields of this hybrid at test locations (8) in Croatia during the 2023 and 2024 growing seasons ranged from 3 918 to 5 552 kg ha^{-1} with average grain moisture contents from 5.0 to 9.8 %.

Figure 1. *KWS Granos* in *classic* sowing technique BBCH 15 (Source: A. Banaj)

Figure 2. *KWS Granos* in *classic* sowing technique BBCH 58 – 60 (Source: D. Mikolčević)

Figure 3. *KWS Granos* in *Twin Row* sowing technique BBCH 13 – 14 (Source: A. Banaj)

Figure 4. *KWS Granos* in *Twin Row* sowing technique BBCH 58 – 60 (Source: D. Mikolčević)

Agrotechnical measures in the production of oilseed rape

The area at the *Tenja* experimental field in the 2021/2022 growing season was sown with winter wheat. The production of oilseed rape began on July 19, 2022, with basic tillage and the application of NPK 8:20:30 mineral fertilizer at a rate of 400 kg ha^{-1}. Pre-sowing preparation and then sowing were carried out on September 23, 2022. Autumn crop protection against weeds and insect attacks was carried out 15 days after emergence (October 10, 2022). During March 2023, four insect protections were carried out as well as disease protection using the fungicides *Pictor* (by BASF) and *Propulse* (by Bayer) in the same ratio at 50 % of the manufacturer's recommendation. Spring fertilization was carried out in the form of two applications: the first using 150 kg ha^{-1} UREA 46 % N at the end of January and the addition of mineral fertilizer KAN at 220 kg ha^{-1} at the end of February. The total amount of nutrients distributed at the Klisa experimental site during the research was 160.4 kg ha^{-1} N, 80 kg ha^{-1} P_2O_5, and 120 kg ha^{-1} K_2O.

RESULTS AND DISCUSSION

On the test plots of the Faculty of Agrobiotechnical Sciences Osijek (N 45°29'55.0032'' E 18°48'16.9092''), the harvest of oilseed rape was carried out on June 30, 2023, using a John Deere S660i universal combine harvester. After harvesting the test plots, the oilseed rape grain was unloaded into a tractor trailer and weighed with a precise field scale. During unloading, grain samples were taken to determine the hectoliter mass and current grain moisture for further laboratory processing.

Figure 5. Rapeseed harvesting by John Deere S660i (Source: D. Mikolčević)

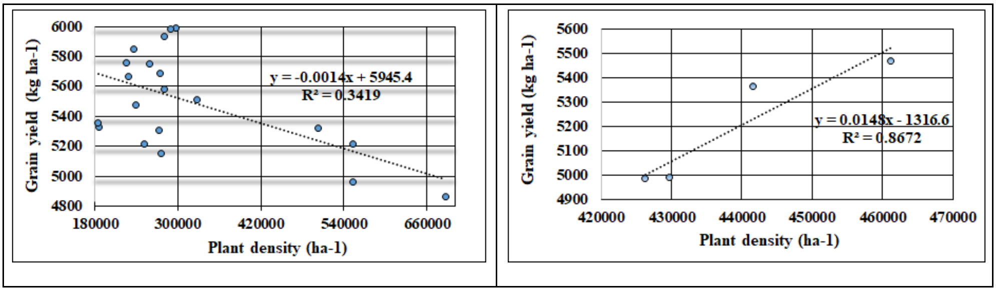
The obtained results of the weight of rapeseed grains depending on the plant density per hectare are shown in Table 4.

Table 4. Achieved grain yield results kg ha^{-1} KWS Granos oilseed rape

Set of plants (ha^{-1})	Grain moisture (%)	Grain yield* (kg ha^{-1})	Hectoliter mass of grain (kg hL^{-1})	Oil content in seeds (%)	Oil content in dry matter (%)
Twin Row sowing					
686 520	8.9	4 861	64.42	47.49	50.58
552 896	7.8	5 217			
552 356	7.7	4 963			
502 647	6.8	5 324			
327 569	8.1	5 512	65.34	46.84	47.72
296 875	7.5	5 993			
289 876	7.4	5 982			
279 897	8.1	5 585			
279 845	7.5	5 935	59.42	47.52	50.58
275 389	8.0	5 149			
274 689	7.5	5 685			
273 142	7.3	5 308			
259 521	7.3	5 754	66.36	46.75	49.51
251 654	7.4	5 214			
239 437	7.2	5 474			
235 897	7.3	5 848			
229 234	7.1	5 668	58.28	46.79	49.89
225 657	7.3	5 758			
186 547	7.2	5 331			
185 121	7.0	5 356			
Standard sowing (50 cm)					
441 569	8.6	5 364	56.68	44.43	47.57
461234	8.8	5 469			
426 289	7.8	4 986			
429 657	8.4	4 989			

*- grain moisture 9 %,

From Table 4., it can be observed that the hybrid rapeseed KWS Granos, at 686 520 plants per hectare in twin row sowing, achieved the lowest yield in the experiment of 4 861 kg per hectare. In contrast, plant densities of 55 plants per square meter at harvest time ensured grain yields ranging from 4 963 to 5 217 kg per hectare. Conversely, a plant density of only 18.5 plants per square meter achieved an exceptionally high grain yield of 5 356 kg per hectare. The highest grain yield in the experiment at the FAZOS trial site of 5 993 kg per hectare was achieved with 29.6 plants per square meter. According to the KWS company's catalog for 2022, rapeseed grain yields in the Republic of Croatia ranged between 3.5 to 5.5 tons per hectare, depending on climatic conditions, fertilization amounts, and other agronomic measures implemented.



Graph 2. Regression line of the impact of sowing pattern on grain yield kg ha^{-1} (twin row sowing – right and standard sowing – left)

CONCLUSIONS

Based on the results of the KWS Granos rapeseed sowing, conducted at the Tenja site (N 45°29'55.0032'' E 18°48'16.9092") at the experimental field of the Faculty of Agrobiotechnical Sciences in Osijek during the 2021/2022 growing season, it can be concluded that smaller plant densities per hectare, ranging from 18.5 to 32.7 plants per square meter, achieved statistically higher grain yields.

- The highest grain yield was recorded at a plant density of 296 875 plants per hectare, amounting to 5 993 kg per hectare.
- Similarly, the group of plant densities from 185 121 to 275 389 plants per hectare achieved yields over 5 300 kg of grain per hectare.
- The lowest recorded yield in the experiment was at a plant density of 686 520 plants per hectare, or 68.6 plants per square meter, amounting to 4 861 kg per hectare with a grain moisture content of 8.9 %.
- The highest oil content in dry matter of 50.58 % was found in plant densities from 52.3 to 68.6 plants per square meter.
- The lowest oil content in dry matter of 47.72 % was recorded in the densities with the highest yield, i.e., from 27.9 to 32.7 plants per square meter.

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50. ACTUAL TASKS ON AGRICULTURAL ENGINEERING

Review paper

BIOMETHANE USE FOR TRACTORS

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ABSTRACT

Biomethane use in agriculture can reduce important dependence on fossil fuels in production and processing of different agricultural products. With biomethane use for agricultural machinery, it will be possible successfully to great extent decarbonize agricultural production in the next decades. Of all biofuels, biomethane has also the lowest carbon footprint and it can also be mixed with natural gas in different proportions. In addition to the compressed form of biomethane, in the future it will also be possible to use a liquefied form of biomethane on some versions of tractors and working machines. After the end of life cycle, recycling of biomethane powered engines is practically very similar as recycling of diesel engines. Possible projections for the introduction of biomethane for use with tractors in Slovenia in the next decade, was made. One scenario is that a certain number of tractors in use (10% of all tractors in use over 60 kW power) could be upgraded in the next decade to the dual fuel system (biomethane and diesel fuel). Hydrotreated vegetable oil (HVO) could also be used to replace mineral diesel fuel (synergistic effect of two biofuels would be achieved). 20 % of new registered tractors of power over 80 kW, that will be gradually introduced over the next decade and beyond, could be: only biomethane powered, with dual fuel type engines (use of biomethane and HVO) or in hybrid version - diesel electric tractors.

***Keywords**: energy, GHG emissions, gas engines, Case Slovenia*

INTRODUCTION

For the EU the goal of achieving climate neutrality (EU Regulation 2021) by 2050 is extremely important, i.e. an economy with zero net greenhouse gas emissions. The modern way of producing food is largely dependent on fossil fuel energy and causes emissions of greenhouse gases and waste by-products. Energy is also a major cost in agricultural production and processing and a financial and environmental burden on the final products of agriculture (Yongxi et al., 2022). Improving energy efficiency by using less energy to ensure the same level of production and services is important to ensure many positive outcomes that can provide multiple benefits: better economy, economic growth, energy security, food security and reduction of GHG emissions. One of the possible solutions for reducing dependence on fossil fuels (IRENA and FAO, 2021) or natural gas is the use of biogas (purified and upgraded biogas to the methane phase - biomethane). Biomethane is becoming more and more important in the field of utilizing alternative energy sources in the EU in recent years. A big advantage of biomethane, compared to some other renewable energy sources, is the possibility of its storage (in gas tanks and natural gas network) and its consumption in terms of energy needs (at any place and at any time). There is also great potential for biomethane storage in the natural gas network (especially during the summer months). With its storage and use, we can successfully compensate fluctuations in other renewable energy sources, such as e.g. water, wind and solar energy. Biomethane can easily be produced at a constant rate and stored, helping to balance the energy supply from other renewable energy sources. The biomethane can be used in several ways: as a raw material in chemical production (Zoltan et all 2017), energetically as a heat source or as a fuel in the form of compressed or liquefied biomethane. By feeding into the gas network, it can also be stored and transported. Working machines and tractors powered by biomethane can have significantly reduced CO_2 emissions (by more than 90%, depending on the substrate source for the production of biogas or biomethane) compared to the use of diesel fuel. Biomethane is not only interesting from the point of view of reducing greenhouse gas emissions (IEA 2020). A biomethane powered engine works more calmly and quietly, and has a longer lifespan due to the clean combustion of biomethane. Biomethane can be used with existing natural gas infrastructure. Bi-fuel engines that use diesel fuel and biomethane can run smoothly on diesel fuel also when the biomethane runs out. The internal combustion engine is the basic drive unit for practically most machines involved in various agricultural productions. Several biofuels are now available that can be used to power agricultural mechanization. In the case of the use of various biofuels, hydrogen and synthetic fuels to drive internal combustion engines, the emissions of harmful substances from the combustion of the mentioned fuels can be significantly reduced or equal to zero (depending on the method of obtaining the mentioned fuels). In addition to the well-known biodiesel fuel, which can be 100% or mixed in different proportions with diesel fuel in the recent period it is increasingly more and more important HVO (Hydrotreated Vegetable Oil). The use of hydrogen and synthetic fuels are still in the development phase for use on tractors. Biogas can also be used to drive work machines and tractors (before being used on engines must be cleaned of various impurities and compressed or liquefied for better use of limited space in vehicles). Cleaned and upgraded biogas – biomethane is identical in composition to methane (CH_4). Biomethane is a fuel that has become quite accessible in recent years, due to the increasing number of biomethane plants (EBA 2024*)* in the EU (1,584 biomethane plants by June 2024). The article presents the current status of biomethane, biomethane emissions, the advantages of using biomethane for vehicles where decarbonization is difficult to achieve with other technologies and the development of biomethane tractors. It also presents possibilities for introducing tractors powered by: biomethane, dual-fuel engines (biomethane and HVO), or hybrid (biomethane and electric powering) in Slovenian agriculture in the future.

LITERATURE REVIEW

Biomethane as the energy content of biogas, or upgraded to the quality of natural gas, accounted for 11 % of the total bioenergy used in the EU 27 in the year 2021. The EU goal is to reach $35 \cdot 10^9$ Nm^3 (~ 337 TWh/year) of biomethane production in 2030 (European Biogas Association, 2022, 2023). The latest data (Eurostat, 2023) report the production of 14.88 M_{toe} (17.71 billion m^3) of biogas in the EU 27 (data for 2021). According to the European Biogas Association (EBA 2024), total biomethane production in Europe reached 4.2 billion m^3 in 2022, showing almost 20 % growth (+ 0.8 billion m^3) on the year, with 1.323 biomethane plants (+ 254 plants). In absolute terms, Germany leads with 1.23 billion m^3 of produced biogas, followed by France (0.66 billion m^3), Denmark (0.61 billion m^3) and Italy (0.41 billion m^3). Looking at the percentage of natural gas consumption in each country that could be covered by biomethane, Denmark and Sweden are on track to largely replace their fossil gas consumption with biomethane (32.4% and 17% covered respectively, in year 2021). In Slovenia, biomethane production at one biogas plant is currently being prepared. The use of fossil fuel-based energy in agriculture causes CO_2 and other emissions (Flammini et al., 2022). Biomethane is the cheapest and easiest form of renewable gas available today. It can also make significant contributions to the energy system tomorrow and also has a very high potential to save greenhouse gas emissions. Until 2030, biomethane will still be mainly produced by anaerobic digestion of waste and biomass residues from agriculture, the food industry and municipal organic waste (Alberici et al., 2021). The majority of European renewable gas production today is in the form of biogas. While total biogas production has stagnated over the last decade, biomethane production is still increasing. Biomethane can immediately provide a strong synergy with the existing gas infrastructure, as it is already suitable for feeding into the existing natural gas network. It thus represents a key element in the identification of medium to long-term solutions for decarbonisation (Orecchini et al., 2011). The authors (Assandri et al., 2022) identified the potential of agriculture to replace diesel fuel with biomethane from organic waste to exploit energy needs and achieve carbon neutrality. As part of the energy transition, some tractor manufacturers have also begun to develop the first solutions that can reduce the impact of tractors on the environment. In addition, biomethane production on farms would represent an excellent opportunity to develop better "circular" systems that produce renewable energy from livestock waste and agricultural waste (Assandri et al., 2022). When evaluating the savings of biomethane emissions produced from slurry, additional aspects must also be taken into account. If not used or in case of storage the slurry would produce CH_4 and N_2O, from natural anaerobic decomposition. These emissions can be avoided by controlling this process in anaerobic digestion and collecting produced biogas (Prussi et al., 2020). The reason for the negative value is that, if the manure is not used for biomethane production, it remains on the farm and releases greenhouse gases also in the form of methane, which has a much greater impact on global warming than CO_2. By producing biomethane, we avoid these emissions and therefore it causes negative emissions (Friedl et al., 2023). For biomethane used on cars, GHG emissions are only from 33 to 66 g CO_{2eq}/km (depending on the raw material used), and for natural gas, 124 g $CO/_{2eq}$ km in the whole life cycle. It depends on the combustion process in the engine but also to the technology of its production. The type of substrate used for methane fermentation has the greatest impact on the reduction of GHG emission in the whole life cycle (Biernat et al., 2021). In addition to using pure biomethane in vehicles, mixing it with natural gas is a smart and cost-effective way to reduce greenhouse gas emissions to meet national targets. Blending the two, even using a low ratio of biomethane to natural gas, can yield a fuel that has significantly lower emissions than regular natural gas. For example, using a blend with 20 % biomethane can save 39 % of greenhouse gas emissions compared to gasoline on a source-to-wheel basis (EBA, 2016). In the EU, several million work machines are used in construction, agriculture, forestry and mining. This class of machinery needs to be decarbonised, like all other sectors. As with heavy road traffic, alternative propulsion technologies must be provided. The energy and power requirements of this group of machines vary greatly depending on the application and size of the machine. As in the road sector, it is also considered that small and light machines are easier to upgrade to electric battery than heavy construction or agricultural machines, which often have very many working hours per year and require high power. If high performance is to be achieved, fuels with a high energy density are preferred. The transition to these fuels is easily possible, as the technology of the vehicle and the fuel supply do not need to be adjusted, or only slightly. Refueling is an important factor for these machines, as they are usually filled at places of operation (tanks on farms or construction sites, etc.) and do not need to be driven separately to gas stations. In general, the choice of decarbonisation option will depend on the specific needs of the application, including factors such as energy requirements, range, infrastructure availability and cost. (Friedl et al., 2023). Heavy vehicles are usually converted to run on methane only, but in some cases dual-fuel engines are also used. The dual fuel engine still has the original diesel fuel injection system, and the gas is ignited by injecting a small amount of diesel fuel. The engine usually idles on diesel fuel. Dual fuel engines usually require less engine development and maintain the same driving characteristics as a diesel vehicle (Wáadysáaw, 2011). Liquefied biomethane is more energy dense, so it is optimal for driving large engines (in heavy road and ship transport) over long distances with minimal storage space and weight (EBA, 2016). Among the technologies for the transport and storage of natural gas and biomethane, the adsorption of gases on porous adsorbents made of solid substances (ANG - Adsorbed Natural Gas) is very interesting (Maryam T. Ravanchi, 2022), because it is cheaper and safer, compared to the classic compression of natural gas or biomethane due to the use of lower pressures (30 – 40 bar) and room temperature. Many solid adsorbents can be used to store natural gas or biomethane. Activated carbon is the most commonly used adsorbent because it is readily available and can be produced from a wide range of precursor materials. Among the various adsorbents, activated carbon is considered the most suitable adsorbent, because it is readily available and can be produced from a wide range of precursor materials (Feroldi at al., 2018). The gas storage capacity in system with lower pressure is even greater than that of the compressed natural gas system, which stores natural gas at a pressure of 200 bars (Park et al., 2018). Activated carbon is used to store natural gas at low pressure, in the range of 20 to 40 bars at room temperature, representing a potential alternative for large-scale applications. This technology is still not well developed and is currently at the research stage.

GAS POWERED VEHICLES IN THE EU

Tractor engines are largely similar in design to truck engines or in some cases identical to engines installed in trucks (in the case of heavy versions of tractors with high power engines). Trucks have been successfully using alternative fuels like natural gas (compressed and liquefied), biomethane and LPG. There is also a well-spread network of filling stations across the EU for the mentioned fuels. In the last few years, the number of filling stations for LNG-powered trucks across the EU also has started to increase (Smajla et all 2019). In order to compare the related field with biomethane, data is given for the number of trucks in the EU powered by an alternative fuel - natural gas. In the EU in the year 2023 in category N2 - vehicles for transporting goods (with a maximum weight of more than 3.5 tons and up to 12 tons) and category N3 - vehicles for transporting goods (with a maximum weight of more than 12 tons) was in use in total 26,236 trucks powered by compressed natural gas (CNG), 9,041 powered by liquefied natural gas (LNG) and 9,899 powered by liquefied petroleum gas (LPG). The total number of all mentioned trucks was 45,176 (European Alternative Fuels Observatory, 2023). For the period from years 2008 to 2024, the total number of trucks powered by compressed natural gas (CNG) was 204,260, and 55,664 trucks powered by liquefied natural gas (LNG). A total of 259,924 trucks powered by natural gas in compressed and liquefied form were in use (these vehicles can also use biomethane). In Slovenia in 2021, 0.4 % of trucks and 4.8 % of buses were powered by natural gas (the EU average for trucks is 0.7 % and buses 3.7 % for the year 2021 (ACEA, 2023). The number of trucks powered by compressed natural gas is steadily increasing from year to year, and the share of trucks powered by liquefied natural gas is also rising in last years. If we add liquefied petroleum gas to compressed and liquefied natural gas, we see that these three types of fuels are dominant in the field of alternative fuels for trucks.

In recent years, several EU manufacturers have already put on the market trucks and buses that can use natural gas and biomethane for propulsion (in some parts of the EU, e.g. Sweden, biomethane powered buses have been present for more than three decades). Therefore, we can say that the field of natural gas for powering trucks and buses is good developed, while the biomethane for powering other vehicles and work machines is in the introduction phase. In addition, the experience in the field of using natural gas for the propulsion of trucks and buses will be able to be applied to other areas in the future, such as e.g. in agriculture and forestry, biomethane for powering tractors and work machines and work machines in construction, mining, utilities, etc.

DEVELOPMENT OF GAS POWERED TRACTORS

The idea of running tractors on gas fuel is not new. It is interesting to note that tractors powered by liquefied petroleum gas (LPG - Liquefied Petrol Gas) were quite popular in the USA from the forties and up to the sixty's years of the last century. There have been many conversions of tractors with petrol engines for LPG use (in a carburetor of a special design, LPG is mixed in a gaseous phase with air in a certain ratio, and mixed gas-air enters to the combustion chamber of the engine). In addition, some manufacturers also offered serial production versions of tractors with engines that used LPG. LPG was cheaper than gasoline, so farmers used it at a bigger scale in the past. With the mass introduction of diesel versions of engines on tractors in the USA, the use of LPG also came to an end. More recently in year 2008, Steyr introduced a tractor with an engine that could run on diesel fuel and compressed biomethane. 400 liters of biomethane were stored under high pressure in the cylinder gas tanks (thick walled pressurized tanks), which was sufficient for a 7 - 10 hour working day. If the biomethane ran out, the tractor engine could also run on diesel fuel. The cylinder gas tanks were placed on the roof of the tractor. The gas came from the tanks through pipes to the control solenoid valve (located on the engine air supply system) in connection with the electronic control unit. The gas entry point (at 4 - 5 bars) was just before the turbocharger to take full advantage of the gas-air mixing effect. The engine starts with diesel fuel, when the engine warms up to operating temperature, the driver presses a button in the cab to activate the gas system. In the second version, the biomethane cylinder tanks were placed next to the rear pillars of the cabin. In 2012, the tractor manufacturer Valtra also presented its version of the Valtra N101 Dual Fuel tractor (it ran on biomethane and diesel fuel). For biomethane storage, it had four cylinder gas tanks with a volume of 42 L, located on the right side of the chassis. The cylinder gas tanks could accommodate 34 m^3 of biomethane under a pressure of 200 bars. An electronically controlled gas injection system allowed precise gas injection into the air intake pipe (as close as possible to the intake valve). When testing and filling the tractor, the idea of removable biomethane tanks also came up. Users could leave the full cylinder gas tanks at the edge of the working areas and replace them with empty ones if necessary, with the help of quick couplings.A new type of biomethane tractor is T6.180 Methane Power, New Holland with engine NEF - N67 NG, developed for agriculture by FPT Industrial (New Holland-Methane Power). Biomethane and CNG can be used as fuel for powering mentioned tractor. The six-cylinder engine with a volume of 6.728 cm^3 develops a maximum power of 128 kW (nominal power of 106 kW).

Figure 1. A tractor that can run on CNG or biomethane, an additional gas tank is also mounted on the front of the tractor (source: New Holland).

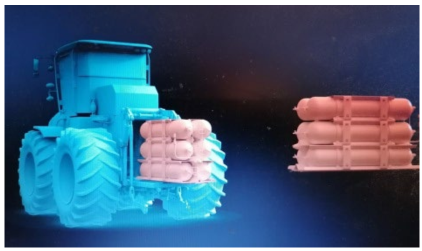

Figure 2. The biomethane cylinder tanks are combined and placed in the rear of the hybrid biomethane tractor AUGA M1, where they are also easily accessible for filling or their complete replacement (source: AUGA).

Gas injectors and spark plugs replace diesel injectors on T6.180 Methane Power tractor. Several gas tanks (use of biomethane or CNG) with a total volume of 185 L are installed on the T6.180 New Holland tractor. The tanks mentioned are filled through one opening, which makes the work much easier for the user (the filling opening is located on the left side of the tractor between the steps). For longer periods between gas fills, there is an additional tank in the front to extend the range (volume 270 L). An interesting concept of a tractor powered by biomethane was presented by the company, AUGA group, Lithuania, which is engaged in agricultural production. They developed the Auga M1 hybrid tractor, which is equipped with a 294 kW gas engine that uses biomethane. The engine is connected to an electric generator that produces electricity for the drive electric motors that are installed in the tractor wheels. The generator charges the battery, which enables short term electric operation of the tractor. The AUGA M1 can operate for up to 12 hours on a single charge of biomethane. There are currently three different prototypes being tested for different work operations. The AUGA group also developed replaceable cylinder gas tanks, which are not filled on the farm, but in the biomethane plants and then transported as replaceable tanks to specific locations located next to cultivated areas.

MODE OF OPERATION OF ENGINES POWERED BY BIOMETHANE

There are already developed versions of reliable industrial engines for using CNG or biomethane which are suitable for tractors of bigger power. In future there will be also in wider use of LNG or liquid biomethane - LBM. In the version of the gas engine that runs only on natural gas or biomethane, the engine works according to the Otto cycle (stoichiometric Otto cycle engine or lean burn Otto cycle engine). To ignite the mixture of gas and air (premixed charge), gas engine needs spark plugs for ignition of mixture in the combustion chamber of the engine. In another system, developed by some manufacturers of gas engines, two types of fuel are used at the same time in engine - dual fuel engines. In the mentioned case, biomethane and diesel fuel are used (mineral diesel fuel, biodiesel B 100 or biodiesel mixed in different proportions with mineral diesel fuel, HVO, etc.). Dual fuel engines can operate with premixed charge of gas and air and diesel fuel pilot ignition (small amount of diesel fuel - up to 15 %, ignite mixed natural gas or biomethane with air). Biomethane, unlike diesel fuel, cannot ignite by itself during the compression phase in the combustion chamber of the engine, so the function of biomethane ignition is performed by diesel fuel. Diesel fuel is injected into the combustion chamber of the engine and ignites at 350 to 380 °C. Natural gas or biomethane, which has a much higher ignition temperature than diesel fuel (ignites at a temperature of approximately 580 to 640 °C) is ignited with smaller amount of injected diesel fuel. Gas injectors for gas injection are controlled with solenoids. The injection of gas is triggered by the electronic control unit with the signal calculated by the engine management system, for precise metering of the quantity of gas required by the engine. Other way of using gas or biomethane in engine is without premixing the natural gas with air. Gas is injected directly into the combustion chamber at high pressure (similar to diesel engine). In this case also ignition source is required. Igniting the natural gas jets in chamber is with a small diesel pilot injection, just prior to the injection of the gas (ignition with glow plug or a pre-chamber spark plug is also being researched). An important benefit of this approach is that higher power density is achievable, and a higher compression ratio can be used. An engine that uses two types of fuel at the same time has better efficiency compared to an engine that uses only one fuel - biomethane. In case of running out of gas, the engine works only with diesel fuel. Emissions of GHG are significantly lower for engines with two types of fuel than for engines powered only with diesel fuel. In the case of using engines with two types of fuel (biomethane and diesel fuel), it is possible to reduce CO_2 emissions by up to 70 % and more (compared to engines that use only diesel fuel). Some manufacturers of tractors and engines started developing tractors and engines for using compressed natural gas or biomethane. New Holland also started regular production of tractors that run on biomethane. In addition to the compressed form of natural gas or biomethane, some tractor engines will also be able to use liquefied biomethane in the future.

USING OF BIOMETHANE FOR TRACTORS IN SLOVENIA IN FUTURE

In Slovenia, according to data from the Ministry of the Infrastructure in year 2023, there are currently 769 vehicles of different types, powered by CNG or combined CNG and another type of fuel (dual fuel engines). Of these, in the category of trucks (N2 and N3 vehicles), there are total of 226 vehicles powered by CNG or combined with CNG and another type of fuel (dual fuel engines). In addition, 95 buses are powered by CNG or combined with CNG and another type of fuel (dual fuel engines). Also 8 tractors are powered with LPG. There are slightly more than 130,000 farm tractors in Slovenia. By analyzing the data on registered tractors in terms of power classes, data from the Ministry of Internal Affairs in 2023, we estimated that tractors with an engine power above 60 kW (total number 25,907 tractors in year 2023) are suitable for upgrading on using biomethane (it is easier to install gas tanks on tractors of higher power (more space is available for gas cylinder tanks, fuel consumption is also higher). From mentioned number of tractors, we assumed that up to 10 % or approximately 2,500 could be upgraded (mainly with government support in whole chain - from biogas production, upgrading biogas to biomethane and distribution biomethane on filling stations) to use biomethane in the next decade. Existing diesel engines of mentioned tractors could be upgraded to the dual fuel system (biomethane and diesel fuel for igniting biomethane). HVO could also be used to replace mineral diesel fuel (a synergistic effect of two biofuels would be achieved). In the event that biomethane runs out, the tractor engines normally operate with HVO or other diesel fuel. 20 % of new registered tractors of power over 80 kW, which gradually will be introduced over the next decade and beyond, could be: only biomethane powered, with dual fuel type engines (biomethane and HVO) or in hybrid version – diesel electric tractors (diesel engines also with use HVO or biomethane). Because of the smaller space, the use of liquefied biomethane - LBM on tractors in the power class between 40 and 60 kW will be better solution (LBM cylinder tanks require less space compared with cylinder tanks for compressed biomethane). In the case of smaller tractors, bellow 40 kW engine power, liquefied biomethane as fuel, due to lower space on tractors, also can be used (we assume in this case also 20 % of all new registered tractors). It will be possible also to use HVO for diesel powered tractors under 40 kW and use of hybrid versions – diesel electric tractors (diesel engines with use of HVO). Small tractors (bellow 20 kW) for light operations, which need smaller amount of power, can be also in electric version.

CONCLUSION

The field of use natural gas for powering trucks and buses is well developed, while natural gas and biomethane for powering other vehicles (tractors and working machines) is in the introduction phase. In addition, experience in the field of using natural gas for the powering of trucks and buses will be able to be applied to other areas in the future, such as e.g. in agriculture and forestry (biomethane for use on tractors and other agricultural machines) and working machines (biomethane for use on construction machines, municipal machines, etc.). Modern new developed versions of biomethane tractors enable continuous operation for several hours. Engines that run on biomethane have also a longer lifespan compared to engines that run on diesel fuel. A big advantage of biomethane is that the tractor cylinder gas tank in fast mode of filling, can be filled at the same speed as with diesel fuel. In addition, biomethane cylinder tank designs are also being developed that enable quick replacement of empty biomethane tanks during various work operations. There are also some disadvantages of using biomethane for powering tractors. A special biomethane filling unit is required. Another solution is a quick and convenient gas replacement (cylinder gas tanks are filled at the biomethane plant, not on the tractor) and delivered to farms. On this way is eliminated need for special biomethane filling units on farms. Tractors with gas engines or a dual-fuel engine for use of biomethane and diesel fuel, are at the moment more expensive than standard tractors with diesel engine of the same power. It is to be expected that the price of biomethane powered tractors will decrease with a greater scope of use. After the end of life cycle, recycling of biomethane powered engines is practically the same as for diesel engines. In addition to the compressed form of biomethane, in the future it will also be possible to use a liquefied form of biomethane in some versions of tractors and working machines.

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50. ACTUAL TASKS ON AGRICULTURAL ENGINEERING

Expert paper

COMPARISON BETWEEN A CLASSIC FORESTRY WINCH AND A CONSTANT PULLING FORCE WINCH

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ABSTRACT

In Slovenia, forestry is a highly developed industry and a vital part of agriculture. Many farms own forests, which provide an additional source of income on the farm. The aim of the paper is to demonstrate the performance of the "constant pulling force" technology used in winches; such tools have been present in the market for quite some time now, but not all users of such machinery are familiar with this technology. For the aim of research, two different winches were tested in the production facilities of the company Krpan. The data obtained enable an easier interpretation of the difference between two different designs of winch systems. The constant pulling force enables the winch an even pull no matter the distance of the load from the tractor. Until now, farmers only used classic winches that do not come with this technology. Now, the new systems facilitate the work of farmers when performing the most difficult agricultural work, such as felling and wood skidding, working in the forest, and in all kinds of work where such a machine is needed. Such machines also have the advantage of facilitating operation on rough terrain, reducing fuel consumption, and increasing safety at work. Based on the literature review and the test results, it has been concluded that a winch with constant pulling force has a more efficient pull than a winch without it, mostly due to choosing the appropriate drive system. The manufacturers are constantly introducing innovations to improve safety at work, especially in hilly, hard to-access areas.

Keywords: *winch, forestry, constant pulling force, pull*

INTRODUCTION

A forestry winch is a key component of a tractor intended for work in the forest. In private forests, so-called adapted agricultural tractors are most often found. As the name suggests, an agricultural tractor has been upgraded in such a way that it is suitable for working in the forest.

These upgrades offer the machine operator greater safety at work, better utilization of the work machine and protection of the work machine. Nevertheless, not all owners of private forests decide on a complete upgrade due to the high cost of a complete upgrade and only partially upgrade the tractor. In this way, they threaten the safety of everyone involved in harvesting wood (Forest-wood, 2020).

Constant pulling force winches already exist in other industries, where advanced sensors, controllers and microprocessors regulate the constant pulling force. The problem is to transfer the technology to robust agricultural machines that are exposed to the most difficult working and weather conditions and to ensure their reliable operation for many years. Their approach to the problem was to oversize the working machine to about one times their rated pulling force. An important role is played by the four-plate clutch, which is hydraulically regulated. The regulator valve is responsible for regulation, which adjusts the pressure in the system depending on the distance of the rope from the drum. The point at which clutch slip occurs due to excessive load weight is adjusted. The goal is that the pulling force of the rope is always the same or constant. For the 6.5 DH model it is 65kN, and for the 8.5 DH model it is 85kN. The solution lies in adjusting the traction power. If the 6.5 DH model has a pulling force of 65kN on the first few wraps, only the one with a higher number of wraps on this model increases constantly to provide 65kn of pulling power. Although the actual pulling power is significantly higher and increases to 120 kN in the last few wraps. At the same time, the pressure in the hydraulic system increases by almost 70 bar to prevent the clutch from slipping. It should be noted that due to the greater pulling force, a larger rope diameter is needed (Dolenšek, 2017).

In the study (Holzfeind et al., 2020) explores the evolution and advantages of using winch-assist systems in forestry, particularly on steep terrains. It highlights how these systems enhance worker safety by reducing the risk of machine rollovers and operator fatigue. Additionally, winch-assist systems help minimize soil erosion and compaction, which are common issues with traditional logging methods. The article also discusses the increased productivity and accessibility to previously unreachable forest areas, making winch-assist systems a valuable tool in sustainable forestry practices.

In the study (Holzleitner et al., 2018) presents a protocol for monitoring the tensile forces in cables used in winch-assist operations on steep slopes. The research involved real-time data collection and analysis to ensure that the tensile forces remained within safe working limits. The findings indicate that winch-assist systems can operate safely without exceeding the tensile strength of the cables, thereby enhancing the safety and efficiency of timber harvesting operations in challenging terrains.

(Omar et al., 2021) investigates the tensile forces in cables used in winch-assisted forestry operations. The study was conducted over four days, monitoring the winch attached to a harvester operating on steep slopes up to 77%. Tensile forces were measured on both the harvester and the anchor machine at a frequency of 100 Hz. Cameras and GNSS devices were used to accurately record the positions of the machines and the timing of operations. The highest measured tensile forces reached 296 kN on the harvester and 260 kN on the anchor machine. The peak forces were observed during slow obstacle negotiation while moving downhill, attributed to the winch's braking system settings. Lower but still significant peak tensile forces were recorded during stationary tasks. However, these peaks were limited to a few events and never exceeded the cable's endurance limit.

In the research (Picchio et al., 2021) is present an improved winching technique aimed at reducing environmental damage during logging operations. Focusing on ecological engineering, the study explores methods to minimize soil and vegetation disturbances typically caused by traditional winching techniques. The enhanced method involves better work organization and advanced equipment, allowing for more precision in moving logs. The primary goal of the study is to reduce the negative impacts on forest ecosystems, which is essential for sustainable forest management.

The purpose of the research is to demonstrate the operation and advantages of the "constant pulling force" technology on forestry winches compared to a classic forestry winch. Constant pulling force technology as a tool has been on the market for some time, but not all users of such work machines are familiar with this technology (Požek, 2021).

MATERIALS AND METHODS

For research purposes, Krpan 8.5 DH winch and Krpan 8.5 EH winch at the end of the production line were tested. The testing took place in the production facility of Krpan d.o.o. in the municipality of Šmarje pri Jelšah. For testing, an apparatus was used (Figure 1) that measures the pulling force of the connected winch in correlation with time.

Figure 1. Device for testing the pulling force of a winch

Winch 8,5 EH used in the experiment

The winch 8.5 EH offers a pulling force of 85 kN and does not have constant pulling force technology. It is a modern version of a traditional winch that has been working and operating in forests for years. It is certainly one of the best-selling models that the company offers. Figure 2 shows winch 8,5 EH. The technical characteristics of the winch are presented in Table 1.

Figure 2. Krpan winch 8.5 EH

Table 1. Technical characteristics of the winch model 8.5 EH (Amon, 2026)

Pulling force	85 kN (8,5 t)
Braking force	106 kN
Medium wire rope speed	0,6 m/s
Standard length and thickness of wire rope	100 m / 13 mm
Maximum length of wire rope	110 m
Recommended tractor power	>59 kW / > 80 KM
Width of the winch	1820 mm
Depth	710 mm
Height with protective net	2310 mm
Height without protective net	1770 mm
Weight (without wire rope)	673 kg
Attachment Category	II., III.
Lower pulley	Serial
Connection	Serial
Hydraulic pulley	Optional
Valve for setting the wire rope unwinding speed	Serial
Remote control	Optional
Moving board for "ramping"	Not possible

Winch 8,5 DH used in the experiment

The 8.5 DH winch is one of two winches that the company produces in its constant pull winch series. The technical characteristics of this model are shown in Table 2. Figure 3 shows winch 8,5 DH.

Figure 3. Krpan winch 8.5 DH

Table 2. Technical characteristics of the winch model 8.5 DH (Amon, 2016)

Pulling force	85 kN (8,5 t)
Braking force	106,3 kN
Medium wire rope speed	0,5 m/s
Standard length and thickness of wire rope	120 m / 13 mm
Maximum length of wire rope	130 m / 13 mm
Recommended tractor power	>62 kW / > 85 KM
Width of the winch	1800 mm
Depth	660 mm
Height with protective net	2310 mm
Height without protective net	1532 mm
Weight (without wire rope)	795 kg
Attachment Category	II., III.
Lower pulley	Not possible
Connection	Serial
Hydraulic pulley	Serial
Valve for setting the wire rope unwinding speed	Serial
Remote control	Optional
Differential gear	Serial
Moving board for "ramping"	Optional

Principle of operation of the winch

Winch hauling is the process of transporting an object (wood) from one place to another. The object being towed is attached to the winch with an arbitrary length of rope on one side. On the other side, the rope is attached to a rotating part called the winch drum. The rotation of the drum allows winding the rope onto the drum and consequently pulling the rope and the attached load (EMCE winches, 2021).

The rope used is placed on the drum in several layers (Figure 4) so that it can provide a sufficiently large reach to the area where the wood is felled. Each successive layer of rope is further away from the axis of rotation of the drum, and as a result, the torque arm, which is marked with the letter r and a number in Figure 4, also increases. As a result, each additional layer of wire means faster winding and pulling. Due to the increased lever, the traction force is reduced. This phenomenon is called drag drop. Although the moment of the lever is constantly changing, a higher pulling force is achieved when there is a minimal amount of rope on the drum and the smallest pulling force when there are many turns of rope on the drum (PLANETA-Hebetechnik, 2021).

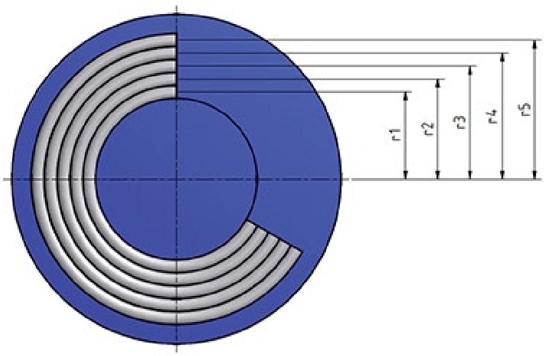

Figure 4. Cross section of winch drum with rope installed

On the schematic diagram (Figure 4), the rope pulling speed can be defined as:

$$v \ = constant * r \tag{1}$$

Where:

v - towing speed
r - torque arm length

The traction force is defined by the equation:

$$\text{Fv} = \frac{\text{constant}}{\text{r}} \tag{2}$$

Where:

Fv - Pulling force
r - torque arm length

RESULTS AND DISCUSSION

The pulling force-measuring device records the data and displays it to the operator in a graphic display. The result of multiple measurements can be presented graphically and explained. In Figure 5, the pulling force measurements made with the Krpan 8.5 EH winch is presented, which does not have constant traction force technology.

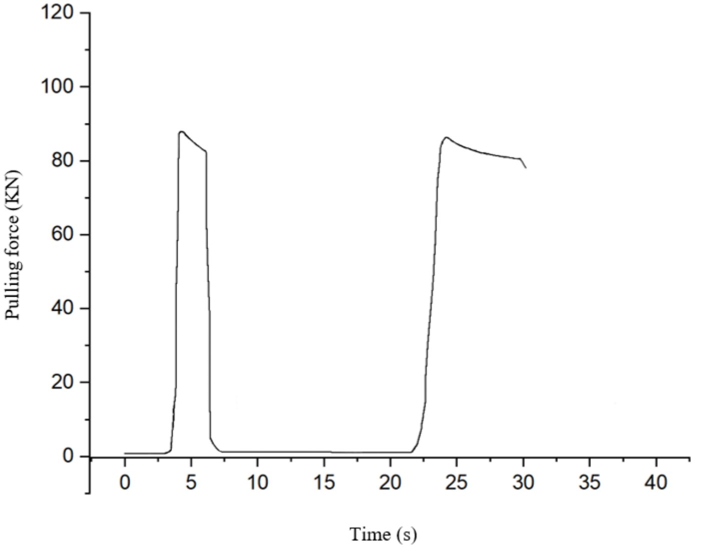

Figure 5. Pulling force of winch Krpan 8.5 EH

The Figure 5 shows that in the fourth second the measured pulling force rises to almost 90 kN. After that, the traction force slowly drops to 83 kN over the next three seconds. The device then stops pulling, so the pulling force between 7 seconds and 22 seconds is equal to 0 kN. At 22 seconds, the device re-engages traction and the pulling force rises again to approximately 86 kN and slowly falls to 83 kN over the next 10 seconds. At 30 seconds, the test is completed and the pulling force drops to 0 kN. It is clear from the figure 5 that a winch like the Krpan 8.5 EH reaches a nominal pulling force of 85 kN and holds it for some time without any problems.

Figure 6 shows the measurement results of the Krpan 8.5 DH winch. As can be seen from figure 6, the winch slightly exceeds its rated pulling force of 85 kN in the fourth second, after which the pulling force drops to 80 kN in the next few seconds. Then the dragging stops. After twenty seconds, the winch pull is re-engaged and the graph reaches 90kN. After a few seconds, the traction force drops to about 80 kN, after which it starts to increase to as much as 110 kN.

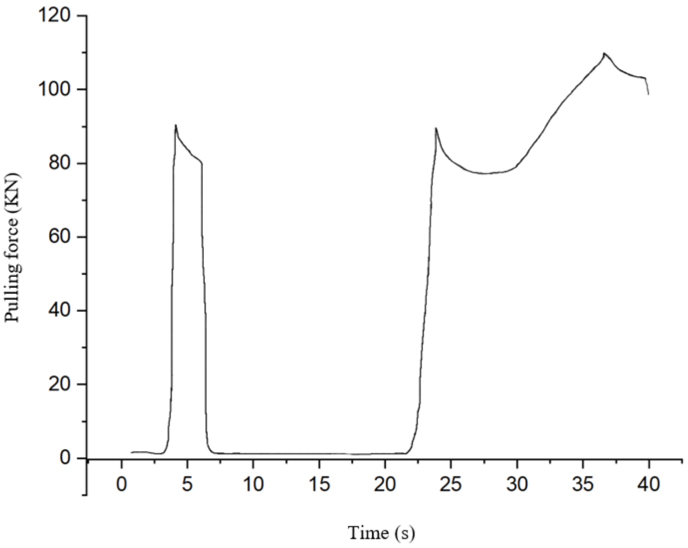

Figure 6. Pulling force of winch Krpan 8.5 DH

The figure 6 perfectly shows in the first part (0-20 seconds) how the winch reaches the rated pulling force and does not cause material collapse of any part of the winch. It is a quick test of the durability and correct construction of the winch at the end of the production line.

The second part of the figure 6 (20-40 seconds) shows the process of increasing the pulling force to ensure the constant pulling force needs of the differently wound drum. The company decided to solve the constant pulling force in such a way that the winches increase the pulling power in order to maintain the declared pulling force of 85 kN. The graph in the second part shows how the pulling force increases from 80 kN at 28 seconds to as much as 110 kN at 37 seconds. This increase of pulling force to 110 kN means that the winch will achieve its rated pulling force of 85 kN even with the drum almost fully wound. After 40 seconds, the test is completed and the pulling force drops to 0.

If figure 5 and 6 are compared, it can be seen that they are very similar. The reason is that in both cases it is a winch that has a rated pulling force of 85 kN. The difference is found in the maximum value of each graph. Figure 6 representing the DH series clearly shows how the pulling force reaches 110 kN without any problems. This test validates the performance of the approach of oversizing winches with constant pulling force so that they can achieve higher pulling force. This higher pulling force, however, maintains the declared pulling force of 85 kN.

These results can also be described from the practical point of view of the tractor operator. When pulling a heavy load, for which a pulling force of 80 kN is needed, both winches would perform the same function with a fully developed drum. It would differ only with a more wound drum at the end of the pull. With an 8.5 DH winch, a constant pulling force would provide the same pulling force with a differently wound drum. With an 8.5 EH winch, however, several turns of rope would drop the pulling force below 80 kN and the pull would stop. The operator should move the forestry tractor further away from the load to allow the drum to re-roll. In this way, it would again exceed the required pulling force of 80 kN.

CONCLUSIONS

Through a literature review and test results, it can be confirmed that a winch with a constant pulling force is more efficient in pulling than one without. From the obtained data, it can be seen that such a winch is more efficient mainly due to the correct selection of the drive system.

By reviewing the literature, obtained is the key information that confirms that continuous innovation aims to improve safety at work. Manufacturers with remote control technology give operators more distance from the work machine when performing towing and remove it from the danger zone. A great example throughout history is also the innovation in ropes used on such work machines, which are safer than ever before in history.

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50. ACTUAL TASKS ON AGRICULTURAL ENGINEERING

Expert paper

TECHNICAL INSPECTIONS OF PLANT PROTECTION MACHINES WITH MOBILE TESTING STATION

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ABSTRACT

The technical inspection of plant protection machinery is regulated by the European Commission Directive on the sustainable use of pesticides (Directive 2009/128/EC) and by the newly introduced ISO standard 16122. This standard was adopted into Croatian regulations with HRN EN ISO 16122 (1-5):2015. According to this standard, all spraying equipment for arable and orchard spraying as well as fixed and semi-mobile sprayers must undergo mandatory technical inspection. Therefore, this paper presents data from the technical inspection of plant protection machines from inspection station No. 004 in the third round of inspections in the period 2021 – 2023 to 2024 – 2026., of which 212 machines were sprayers (machines in arable farming), while 90 machines were air-assisted sprayers or sprayers for the application of bushes and trees. Tractor carried machines accounted for 87.42 % of the machines tested, while 70.20% of the machines were Agromehanika sprayers (56.29%). The average flow rate of all pumps observed in the test station is 99.05 l min^{-1} and 67.88 % of the machines tested have a circular agitation system. Most of the machines are equipped with Lechler ISO nozzles (56.29 %). Tested machine mostly have a length of up to 12 m (53.64 %). The tank capacity is closely correlated with the working width, so that most of the machines tested have a tank volume of less than 600 litres, while the average value is 948.60 litres. The average production year of the machines examined is 2003, i.e. the machines are on average 20 years old. The average CV value of all machines tested is 19.51%, which is clearly at the upper limit of validity.

Keywords: *technical inspection, EN 16122, sprayers, orchard sprayers, plant protection*

INTRODUCTION

Technical inspection of plant protection machinery is regulated by the European Commission's Sustainable Use of Pesticides (SUD) Directive (Directive 2009/128/EC) and by the newly introduced ISO standard 16122 (Inspection of sprayers in use). The SUD is an important regulation to promote the responsible use of pesticides to protect human health and the environment. Its objectives include: Promoting the sustainable use of pesticides; Reducing the adverse effects of pesticide use on human health, the environment and biodiversity; Improving the effectiveness of pest control measures while minimizing reliance on pesticides. This standard was adopted into Croatian regulations by HRN EN ISO 16122 (1-5):2015. According to this standard, all spraying equipment for arable and orchard sprayers, as well as fixed and semi-mobile spraying equipment must undergo mandatory technical inspection. Based on the risk assessment for human, animal and environmental health, the technical inspection is still not required for hand and knapsack sprayers with manual, battery or motor drive and knapsack sprayers with motor drive in fruit growing. This standard also specifies the inspection procedure, the equipment required for testing performance and the software in which all the necessary data is stored. The technical inspection has been carried out in the Republic of Croatia since 2014, where 10 test stations are currently registered. The first results on the condition of the machines come from Banaj, et. al. (2012), who states that the main reason for technical deficiencies are defective pressure gauges and nozzles (up to 60 %). Other European authors reported on the condition of sprayers in their countries, Declercq et al. (2016) state that in the fifth cycle of technical inspection in Belgium (from 2008 to 2010 in Flamania), 1557 orchard sprayers were inspected and only 9.7% (152) of them failed the technical inspection. Spanish authors (Solanelles et al, 2018) stated that the most common defects in inspected sprayers were safety - 24%, defective liquid tanks - 7%, pressure gauges - 28%, filtering system - 13%, nozzles - 13% and other defects - 15%. Analysis of these faults shows that 40% of these machines do not meet the technical inspection requirements. The complete procedure for performing the technical inspection described in the ISO standard is provided by Tadić et al. (2021), and it is evident that most EU countries are implementing the European directive and the mandatory technical inspection of plant protection machinery.

Therefore, this paper presents data from the technical inspection of plant protection machinery of test station 004 in the third inspection round in the time interval from 2021 – 2023 to 2024 – 2026.

MATERIALS AND METHODS

Material and methods for the technical inspection procedure are described in the already known ISO 16122:1-4 standards, which were presented by Tadić et al. (2021) and are available at https://www.iso.org/standard/83366.html (/83368; /83370; /83371). Mobile test station 004 is equipped with an automatic and electronic device for liquid distribution analysis (*AAMS spray scanner*), ultrasonic pump capacity tester (*Krohne*) – Figure 1 a, device for comparing working pressure from sprayers manometer and calibrated manometer (*Volos*), electronic nozzle flow meter (*AAMS*) - Figure 1 b, PTO rotation meter and other devices specified by the ISO standard. Quality of surface liquid distribution is satisfactory when coefficient of distribution (*CV*) is under 20%; Manometers are installed on sprayers with minimal diameter of 63 mm, and with measuring accuracy up to ± 0.2 bar (at test area from 0 to 2 bar). At bigger tested area, test accuracy can be ± 10%. The measuring scale of manometers must be readable and adapted to used working pressures. The permissible deviation of the pump capacity can be up to 10% of the nominal capacity prescribed by the manufacturer. Nozzle flow deviation is allowed within ranges ±10% from marked flow. The detailed technical inspection procedure is explained at *NN 141/2021* available at: https://narodne-novine.nn.hr/clanci/sluzbeni/full/2021_12_141_2389.html.

a.

b.

Figure 1. Ultrasonic pump capacity tester (a.) and nozzle flow testing (b.)

RESULTS

Testing station No. 004 (owned by the Faculty of Agrobiotechnical Sciences in Osijek) tested 302 machines during the three-year testing period from 2021 – 2023 to 2024 – 2026.

Of these, 212 machines were sprayers (machines in arable farming), while 90 machines were air-assisted sprayers or sprayers for bush and tree application (designation from the ISO standard). Most of the machines tested were tractor carried (264), while 32 machines were tractor trailed and 6 were self–propelled. Looking at the manufacturers of the machines, more than half of them are Agromehanika, while 27 are from the manufacturer Leško, 32 from Hardi, 9 from Biardzaki, 17 from MIO, 11 from Metalna Rau and 44 machines from other manufacturers. It is important to mention that in the period from 2022 to 2024, a total of 41 machines were deregistered from the plant protection database (FIS base) of the Ministry of Agriculture. The reason for this is the purchase of a new machine, destruction of the old machine, cessation of agricultural activity, etc. Table 1 provides an overview of the machines inspected. The table of machines tested over a three-year period shows that 70.20 % of the machines are sprayers and 29.80 % are orchard and tree sprayers. In addition, 87.42 % of the machines are tractor-carried and Croatian farmers mainly work with Agromehanika machines (53.64 %).

Closely related to the manufacturer, most of the pumps installed on the machines are BM-branded used by Agromehanika (43.70 % of all pumps tested). Depending on the dimensioned needs and capacity, the pumps are usually equipped with a flow rate of 60 to 100 l min^{-1}. The average flow rate of all pumps observed in the test station is 99.05 l min^{-1}, while the interval of the limit flow rates is between 41 and 482 l min^{-1}. The agitation system is closely related to the aggregate system and the tank capacity. Most machines with a larger tank have a hydraulic agitation system. Accordingly, 67.88 % of the machines examined have a circular agitator system. Table 2 shows the type of pumps, their capacity and the agitation system of inspected machines.

Table 1. An overview of the tested machines

Test station no. 004 – Faculty of Agrobiotechnical Sciences Osijek						
Time interval – One testing period (3 years) from 2021 – 2023. to 2024 – 2026.						
No. of tested machines 302						
No. of sprayers				No. of sprayers for bush and tree crops		
212				90		
Manufacturers (*n*)						
Agromehanika	*Leško*	*Hardi*	*Biardzaki*	*MIO*	*Metalna Rau*	Others
162	27	32	9	17	11	44
Aggregation system (*n*)						
Carried		Trailed			Self-propelled	
264		32			6	
Logout machines from the FIS system – from 2022 – 2024.						
41						

Table 2. Pumps and agitation on tested machines

Most represented pumps – type (*n*)						
BM 65/30	BM 105/20	BM 150/20	BM 2	KM 65/30	*Comet* pumps	*Hardi* pumps
86	8	6	32	18	18	32
Average pump capacity		Min. capacity			Min. capacity	
99,05 l min^{-1}		41 l min^{-1}			482 l min^{-1}	
Agitation (*n*)						
Hydraulic				Circular		
97				205		

The nozzles are the most important and most responsible element of overall plant protection system and have a major influence on technical correctness, which is why they are at the forefront of technical control (Tomantschger et al., 2021). It is very important that the nozzles are within 10 % of the original flow rate, i.e. they must not be clogged or worn out. There is a whole series of different types and manufacturers on the market, and it is very important that the inspector can recognize and systematize them. As this is already the third round of technical inspection, farmers are aware of the importance of nozzles and have started to equip their machines with nozzles from renowned manufacturers (Lechler, Albuz, TeeJet), so that, for example, 56.29 % of the technically inspected machines are equipped with Lechler nozzles. The nozzles are often mounted in an exchangeable bayonet system (46.35 % of all machines in the technical inspection), so that a machine usually has nozzles with several ISO numbers that are required for different purposes. The most commonly used ISO nozzle types range from ISO 02 to ISO 04, i.e. each of the machines surveyed had one of these nozzles fitted. However, it can be stated that ISO 04 nozzles are the most commonly used (in 140 cases). However, there are many nozzles on the market that are not dimensioned with the ISO 10625 standard according to the original flow rates, such as Albuz nozzles. Very few special pneumatic nozzles are represented (3 cases) and John Deere twin fluid nozzles (3 cases). It is important to note that there are still many obsolete machines on the market that only use ceramic tiles as nozzles (16 cases). Table 3 shows all nozzle characteristics of the tested machines.

Table 3. Nozzle properties on tested machines

Combination of nozzles (*n*)							
Multi-place system				Single mount system			
140				162			
Most represented ISO nozzles (*n*)							
ISO 01	ISO 015	ISO 02	ISO 025	ISO 03	ISO 04	ISO 05	ISO 06
1	22	98	17	80	140	5	23
Out of ISO standard (*n*)							
JD twin fluid	Albuz nozzles	Ceramic tiles	Hardi nozzles	Pneumatic			
3	32	16	3	3			
Most represented manufacturers (*n*)							
Lechler	*TeeJet*	*Albuz*					
170	42	32					

Looking at the dimensions of the machines used in Croatian agroecological conditions, it can be seen that most of the machines are with relatively small working widths. Most of the observed machines have a working with of up to 12 m – 16.89 % up to 7.5 m; 23.50 % up to 10 m and 13.25 % up to 12 m. The total number of machines with a working reach of up to 12 m is therefore 53.64 %. It can also be seen that station 004 inspected 32 machines with a working range of more than 20 m, most of which belong to the largest Croatian agricultural companies with the most cultivated land – Vupik plus, Belje plus and PIK Vinkovci plus.

The tank capacity is closely correlated with the working width, so that most of the machines examined have a tank capacity of less than 600 litres, while the average value is 948.60 litres. Specifically, there is 1% of machines with a tank capacity of less than 300 l, 34.77 % of machines with a tank capacity of less than 400 l and 29.80 % of machines with a tank capacity of 400 – 600 l.

The age of the machines is not very representative by Croatian standards, as the average production year of the machines surveyed is 2003, i.e. the machines are on average 20 years old. The largest number of machines is in the 2000 – 2010 range with 36.09 %. Of particular concern are machines older than 1990, namely 17.88 %. Table 4 shows the tank capacity, working width and production year of tested machines.

Table 4. Tank capacity, working width and production year of tested machines

	Tank capacity (l)							
	< 300	300-400	400-500	500 - 600	600 - 1000	1000 - 2000	2000 - 3500	> 3500
n	3	105	66	24	33	34	33	4
Average	948.60							

	Working width (m)					
	5 – 7.5	7,5 – 10	10 – 12	12 – 15	15 – 24	> 24
n	51	71	40	18	27	5
Average	12.43					

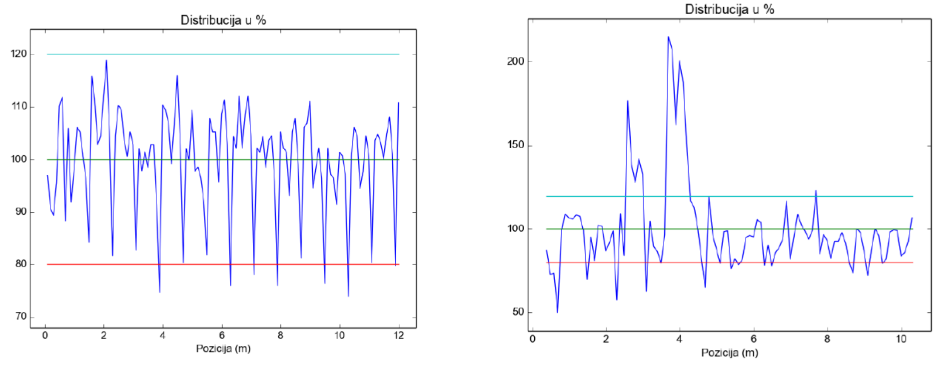
	Production year							
	2020 – 2024	2015 – 2020	2010 – 2015	2005 – 2010	2000 – 2005	1995 – 2000	1990 – 1995	< 1990
n	25	35	26	65	44	18	35	54
Average	2003							

The last and most important step in the technical inspection of sprayers is to check the horizontal liquid distribution. According to Croatian regulations, machines must have a distribution variation coefficient of less than 20 in order to pass the technical inspection (measured under outdoor conditions). The inspector has the option of marking "minor defect" for machines with a value of slightly higher than 20 %, and the machine passes the technical inspection. However, for machines with a CV of more than approx. 25%, the machines are sent back for re-inspection when the defects have been rectified. This is usually the case if the nozzles are clogged or worn, if the boom had nozzles with different ISO numbers or if the nozzles do not overlap well, i.e. the streams are not bevelled at an appropriate angle. The average CV value of all machines tested is 19.51 %, which is clearly at the upper limit of validity. Most of the tested machines (33.44 %) had a CV value in the range of 15 – 20 %, while 17.21 % had unsatisfactory values. Table 5 shows the CV for the machines tested.

Table 5. Liquid distribution of tested sprayers

	Liquid distribution – Coefficient of distribution – CV (%)					
	< 5	5 – 10	10 – 15	15 – 20	20 – 25	> 25
n	0	17	42	101	25	27
Average	19.51					

The test station uses an automated device (AAMS Spray Scanner) to measure the horizontal distribution of the liquid, and Figure 2 shows two results from the technical inspection: a - satisfactory distribution of the liquid (CV = 13.88 %, working width 12 m); b - unsatisfactory liquid distribution (CV = 28.80 %, working width 12 m). On Figure 3 is shown orchard sprayer at nozzle flow check (a) and sprayer at horizontal liquid distribution check (b).



a. b.

Figure 2. Horizontal liquid distribution

a. b.

Figure 3. Nozzle flow and liquid distribution check

CONCLUSION

The test station of the Faculty of Agrobiotechnical Sciences (No. 004) has been involved in the technical inspection of plant protection equipment for many years as part of its professional activities. In the past third round of the three-year cycle, it inspected 302 machines, mainly in the Pannonian part of the Republic of Croatia. As far as the location of the machines and cultivation systems is concerned, the inspected machines are mainly tractor-carried types intended for use in arable farming. More than 50 % of the inspected machines are from the manufacturer Agromehanika, and farmers consider these machines to be reliable, easy to operate and affordable. As far as the aggregate system is concerned, the machines are mostly equipped with a circular agitation system, with an average pump capacity of 99.05 l min^{-1}. The machines mostly use nozzles from the manufacturer *Lechler* in the bayonet system, with the most commonly used nozzles having ISO numbers 02 to 04. Taking into account the above-mentioned production conditions and the average size of the cultivated area, the machines have smaller working widths (usually up to 12 m) and tank capacities of 400 - 600 litres. The indicator of the horizontal distribution of the liquid (coefficient of variation) is on average at the upper limit of validity (19.51 %), which is due to poor adjustment of the machine and maintenance of the nozzles. Finally, it is very important to mention the worrying fact that the machines have a long lifespan, over 20 years, with an average production date of 2003. For this reason, many farmers are taking their machines out of service because they are giving up farming (41 machines from 2022-2024).

From a scientific point of view, the capacity of the machines (working width and tank capacity) must be increased in order to increase productivity and reduce costs. Accordingly, it is necessary to acquire technologically new machines and invest additional efforts in the maintenance of the machines.

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EFFECT OF DIFFERENT TILLAGE SYSTEMS ON SOIL COMPACTION AND WINTER WHEAT YIELD

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ABSTRACT

In the last years, Slovenian farmers are showing higher interest in conservation tillage systems into their practices due to the more frequent extreme weather conditions and the need to optimize work processes in agriculture. The purpose of this study was to examine the advantages and disadvantages of different soil cultivation systems for sowing of winter wheat on the field covered with corn straw. The experiment included four different methods of soil cultivation and preparation: ploughing (CT), disc harrowing (DH), tine cultivator (TC), and no-till system (NT). The number of emerged plants was significantly lower in NT (78%), while there was no difference between CT, DH and TC, respectively. The highest yield was in the DH (6.54 t ha^{-1}) but it was not statistically different from the CT (6.50 t ha^{-1}) and TN (6.17 t ha^{-1}). When estimating soil compaction in the depth of 5 cm to 30 cm, the highest average value was measured after first fertilisation in NT (3.50 MPa). The results of the study indicate that non-ploughing systems can provide comparable and high-quality grain yields of winter wheat. We believe that in the future, alternative soil cultivation methods will become increasingly widespread in our region, including smaller and medium-sized farms.

Keywords: *Conservation tillage, No-till, Soil compaction, Winter wheat*

INTRODUCTION

On a global scale, the areas cultivated in the conservation tillage system are constantly increasing. The growth of areas without ploughing started to increase especially rapidly after 1990. Since 2008, conservation agriculture has increased by more than 10 million hectares annually (Kassam et al., 2019), so after ten years conservation agriculture expanded to 205.4 million hectares, which is 14.7% of the world's cultivated land (Kassam et al., 2021).

According to Biberdžić et al. (2020) different tillage systems can affect soil compaction, water content, soil temperature, and yields of cultivated plants. In the two-years experiment the highest yield of winter wheat was measured in the conventional tillage system (4033 kg ha^{-1}), and it was significantly higher than the disc harrowing and no-till (Biberdžić et al., 2020). After four-year experiment Jug et. al (2011) concluded that chiselling (CH) and disc harrowing (DH) gained equal grain quantity and quality properties as conventional tillage (CT) on chernosem type of soil, while the yield was mostly effected by different whether conditions.

In Slovenia, we are lagging behind global trends in the introduction of conservation tillage. Nevertheless, no-till systems are gaining more and more attention, especially on medium-sized farms and agricultural enterprises, where they mostly introduced this method of tillage. In addition to improving soil fertility, conservation agriculture contributes to reducing the consumption of working time and energy on farms (Jakop, 2022).

The positive effects of conservation tillage can also be seen in a long-term experiment that has been taking place in Moškanjci on lighter soil since 1999 and in Ljubljana on heavier soils since 2000. There, as part of testing different systems of basic soil tillage, it was found that the soil in conservation tillage method of soil cultivation increased the content of organic carbon in the upper layers. The results of the project also showed that lighter soils are more suitable for the transition to conservation farming (Mihelič, 2023). According to Mihelič et al. 2024, The long-term tillage experiment’s transition from conventional to organic management resulted in an increase in soil C stocks and microbial biomass, accompanied by a shift in microbial community composition in the top 10 cm of soilunder the non-inversion minimum tillage (MT). Notably,

SOC levels remained constant under conventional ploughing (CT) even during the 5 years following the conversion to organic farming, emphasizing the importance of implementing non-inversion reduced tillage practices for SOC accumulation.

The main goal of this research was to find most suitable soil tillage for replacing conventional tillage in producing of winter wheat on more economical, less time-consuming and environmentally friendly way on lighter soil type in the Pomurje area (Slovenia).

MATERIAL AND METHODS

Experimental design

An experiment of different soil tillage systems with a corn-straw residues for sowing winter wheat took place in Pomurje, near the village of Srednja Bistrica (Lat. 46°32'41,71" N; Long. 16°17'18,22" E), on a deep alluvial eutric soil. The soil contained 8.07 mg of P_2O_5 per 100 g of soil, 14.91 mg of K_2O per 100 g of soil, 45.2 g of humus per 1 kg of soil and pH value 6.72.

The size of the experimental field is 1.44 ha and is part of the 2.64 ha field. The experiment was designed according to a randomized block design with four treatments and four replications: plough (CT), disc harrow (DH), tine cultivator (TC), and no-till planter (NT). Each plot is 100 m long and 9 m width (90 m^2). The size of the plots was designed based on the working widths of the agricultural machines used in the experiment (Figure 1).

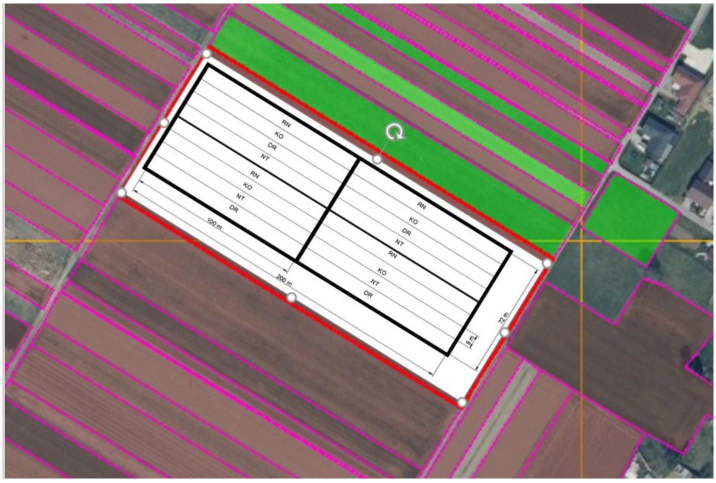

Figure 1. Design of experimental plots in the experimental field on the Škrobar farm.

On October 2023 winter wheat (*Triticum aestivum* L.) Obiwan (SIS, societa italiana sementi) variety was planted in the experiment with the sowing rate of 200 kg ha^{-1} (400 grains/m^2). The variety is classified as a short-growing variety that ripens early. It belongs to the bread varieties and is suitable for lighter soil types.

Machines used in the experiment

Firstly, the entire surface of the experimental field was first mulched using a hummer drill Tierre Pantera 280 mulcher (Tierre) with a working width of 2.8 m. In the conventional method of cultivation (CT), a four-furrow reversible plough Lemken Variopal 6 equipped with strip plough boards for lower energy consumption was used. The average soil plowing depth on the farm is 0.20 m.

For disc harrowing (DH), an Evodisc 300 (Özdöken) was applied, equipped with two consecutive rows of discs with a diameter of 0.56 m. The distance between the rows is 0.95 m, which allows a good flow of plant residues. A toothed roller is installed on the back of the tool, which regulates the working depth and also compacts soil that is too loose. The working depth is hydraulically adjustable and averages 0.12 m.

For NT treatment, a Great Plains 3P1006NT (Great Plains) direct seed drill was used, which has a special cutting disc installed in front of each seeding unit for the penetration of the seeding unit through the harvest residues to the optimal seeding depth. The distance between individual sowing elements was 0.19 m.

Contrary, sowing on the CT, DH and TC treatments was done with a combination of mechanical seed drill Kverneland NG 300 M4 (Kvernerland) equipped with disc seeding elements and a rotary harrow. The rotary harrow has installed working elements in the form of prongs, which effectively break up soil clods with circular movements. A toothed roller for soil compaction is installed on the rotary harrow, and it also serves to regulate the constant working depth.

After seeding several agro-technical measures took place as it is listed in Table 1.

Table 1. Fertilisation and plant protection measures

Date	Agro technical measure	Description
October 11, 2022	UREA for straw mineralisation	UREA (46 % N) – 80 kg ha^{-1}
November 11, 2022	Herbicide	Trinity 1.8 l/ha – 200 l ha^{-1}
February 22, 2023	1st fertilization	KAN (27 % N) – 180 kg ha^{-1}
March 23, 2023	1nd fertilization	UREA (46 % N) – 100 kg ha^{-1}
April 24, 2023	1rd fertilization	UREA (46 % N) – 100 kg ha^{-1}
April 26, 2023	Fungicide	Priaxor 1.4l/ha – 200 l ha^{-1}
April 26, 2023	Growth regulator	Moddus evo 0.4l – 200 l ha^{-1}
May 30, 2023	Fungicide	Prosaro 0.95l – 200 l ha^{-1}

Measurements and sampling

30 days after sowing, the number of established plants and on February 22, 2024 the number of overwintered plants was counted, respectively. The number of spikes/m^2 was counted before harvest.

To determine the grain yield, 2 m^2 on each plot in all repetitions were harvested with the wooden model and a hand saw, and afterwards put into the bags. After the harvest on July 25, 2024, the bags with plants were transported to the Agricultural Institute of Slovenia (Jable), where the wheat was threshed on a threshing machine for experimental purposes (Wintersteiger, Austria).

The samples were additionally cleaned and weighed. The quality of the wheat grain was evaluated on the Perten device for the protein content, hectolitre weight and sedimentation value of the produced winter wheat grain.

Soil compaction was measured with a hand penetrometer Eijkelkamp (Royal Eijkelkamp). The measurements were made before the first fertilization of winter wheat and at the end of the growing season, to a depth of 30 cm, with a step of 5 cm by using a tip no. 2 with a cone area of 2 cm^2.

Statistical analysis

All statistical analyses were performed using Statgraphics Centurion VX (2015), using two-way analysis of variance (ANOVA) for the interaction effects of factors on the dependent parameter. When an interaction effect was not confirmed, one-way ANOVA was used for interpreting the effects of each individual factor. The differences in the content levels were estimated by Duncan's test. P-values of less than 0.05 were considered statistically significant.

RESULTS AND DISCUSSION

Soil compaction after first fertilization

Table 2 shows data on average soil compaction to 30 cm on every 5 cm depth layer in different treatments, after first fertilization and harvest of winter wheat, respectively. After first fertilisation soil compaction was statistically different between tillage systems up to a depth of 20 cm, while in a depth of 20-30 cm soil compaction did not differ statistically significantly. It can be seen that the average soil compaction increased with soil depth regardless of tillage system. The highest average soil compaction in the depth of 5 cm to 30 cm was recorded in NT (3.50 MPa), while in DH (2.98 MPa) and TC (2.74 MPa) there was no statistically significant differences. The average lowest compaction was measured in CT (2.02 MPa). Similar results were also obtained by Biberdžić et al. (2020), who investigated the influence of the tillage system on soil compaction and yield of winter wheat. In a three-year experiment in Serbia, the highest compaction was measured throughout all studied years in no-till (1.87–2.47 MPa) compared to conservation and conventional tillage.

Table 2. Average soil compaction (MPa) after first fertilization and harvest in four different tillage systems

	After first fertilisation				After harvest			
	Soil tillage							
Depth	CT	TC	DH	NT	CT	TC	DH	NT
5 cm	0,16 ± 0,10$^{b\,B}$	0,74 ± 0,16$^{ab\,B}$	0,71 ± 0,30$^{ab\,B}$	1,40 ± 0,39$^{a\,B}$	1,66 ± 0,08$^{b\,A}$	1,65 ± 0,15$^{b\,A}$	1,54 ± 0,07$^{b\,A}$	2,21 ± 0,12$^{a\,A}$
10 cm	1,15 ± 0,02$^{b\,B}$	2,46 ± 0,25$^{a\,A}$	2,67 ± 0,26$^{a\,A}$	3,23 ± 0,55$^{a\,A}$	2,25 ± 0,10$^{bc\,A}$	2,04 ± 0,21$^{c\,A}$	2,65 ± 0,27$^{b\,A}$	3,04 ± 0,07$^{a\,A}$
15 cm	1,22 ± 0,19$^{b\,B}$	2,98 ± 0,19$^{a\,A}$	3,36 ± 0,47$^{a\,A}$	3,88 ± 0,51$^{a\,A}$	2,28 ± 0,17$^{a\,A}$	2,25 ± 0,13$^{a\,B}$	2,85 ± 0,33$^{a\,B}$	3,10 ± 0,23$^{a\,A}$
20 cm	1,85 ± 0,21$^{b\,A}$	3,14 ± 0,17$^{a\,A}$	3,19 ± 0,33$^{a\,A}$	3,75 ± 0,60$^{a\,A}$	1,96 ± 0,11$^{b\,A}$	2,18 ± 0,14$^{b\,B}$	3,00 ± 0,18$^{a\,A}$	3,10 ± 0,09$^{a\,B}$
25 cm	3,39 ± 0,24$^{a\,A}$	3,20 ± 0,25$^{a\,A}$	3,73 ± 0,72$^{a\,A}$	4,26 ± 0,33$^{a\,A}$	2,84 ± 0,30$^{a\,B}$	2,41 ± 0,20$^{a\,B}$	2,92 ± 0,23$^{a\,A}$	3,19 ± 0,14$^{a\,B}$
30 cm	4,35 ± 0,36$^{a\,A}$	3,91 ± 0,22$^{a\,A}$	4,24 ± 0,65$^{a\,A}$	4,51 ± 0,08$^{a\,A}$	3,13 ± 0,12$^{a\,B}$	2,95 ± 0,11$^{a\,B}$	3,05 ± 0,27$^{a\,B}$	3,04 ± 0,11$^{a\,B}$
Average	2.02$^{c\,B}$	2.74$^{b\,A}$	2.98$^{b\,A}$	3.50$^{a\,A}$	2.35$^{c\,A}$	2.25$^{c\,B}$	2.67$^{b\,A}$	2.95$^{a\,B}$

^{a,b,c} significant difference between tillage systems after first fertilisation/harvest (Duncan α = 0,05),
^{A,B} significant difference between the same tillage systems after first fertilisation/harvest (t-test α = 0,05)

Soil compaction after harvest

The highest average soil compaction after harvest was again in NT (2.95 MPa), followed by DH treatment (2.67 MPa) CT (2.35 MPa) and TC (2.25 MPa). When comparing these results with the one after first fertilization, the values between the soil tillage systems at the end of the growing season have decreased considerably. In the NT, the highest compaction regardless of the depth compared to the other treatments was measured again. There were no differences between CT compaction at a depth of 5 and 10 cm compared to DH and TC. Contrary, at a depth of 20 cm, compaction at CT was the same as at TC and significantly lower than DH.

When dealing with CT, the average soil compaction increased the most between the first and second measurements. The average compaction at a depth of 5–30 cm was 2.02 MPa during top dressing, and 2.35 MPa after harvesting. Many studies have come to similar conclusions that soil density in the upper soil layer decreases for a short time after ploughing, but increases again during vegetation (Karlen and Logsdon, 2004).

Growth and development of winter wheat

Table 3 shows the growth and development of winter wheat throughout the growing season. The least number of plants emerged in the NT treatment (306 plants/m^2), which is equvalent to 76.5% of the sown germinating grains. Other tillage methods had the same statistically significant effect on the emergence of plants. On average, 98% of plants emerged in CT, 95.8% in DH and 96% in CT. The reason for weaker emergence when treating NT is partly attributed to greater soil compaction in the upper soil layer, and partly to the large amount of harvest residues on the surface. Biberdžić et al. (2020) state that an excessive amount of crop residues on the soil surface can negatively affect seed germination and inhibit initial plant growth.

From the results on the growth and development of the crop in the experiment, lower values at NT considering the emergence of plants and the number of spikes are recorded. In NT system, it would be good to increase the sowing rate, so a greater number of plants could be achieved. It is assumed that, despite the increase in the sowing rate, crop development in the NT system would be slower compared to the other treatments, due to greater soil compaction.

During the winter period, an average of 1.8% of plants died. Slightly more plants died over winter in the CT treatment (4.6%) compared to the other treatments, but this did not affect the statistical differences compared to the DH and TC treatments. Even after wintering, the NT treatment was characterized by the lowest number of plants (302 plants/m^2) compared to DH (382 plants/m^2), TC (380 plants/m^2) and CT (374 plants/m^2) which is most likely due to the lower number of plants after emergence. The similar effect of different tillage method on the winter wheat emergence (Yu et al., 2023). The yield of winter wheat grain with 14% moisture was statistically significantly higher in the DH (6.54 t ha^{-1}), CT (6.50 t ha^{-1}) and TC (6.17 t ha^{-1}) treatments than in the NT treatment (5.29 t ha^{-1})

Table 3. The influence of the soil tillage on the growth and development of winter wheat

Soil tillage	Number of emerged plants (plants/m^2)	Number of plants after wintering (plants/m^2)	Number of spikes (plants/m^2)
CT	392 ± 3,4^a	374 ± 0,8^a	732 ± 22,0^b
TC	384 ± 10,7^a	380 ± 5,8^a	784 ± 55,8^{ab}
DH	383 ± 6,2^a	382 ± 4,4^a	828 ± 12,0^a
NT	306 ± 18,2^b	302 ± 8,6^b	544 ± 26,5^c

^{a,b,c} significant difference between tillage systems after first fertilisation/harvest (Duncan α = 0,05).

Yield and grain quality of winter wheat

Table 4 shows the yield and grain quality data of winter wheat. The highest yield was in the DH treatment (6.54 t ha^{-1}), but it was not statistically different from the CT (6.50 t ha^{-1}) and TN (6.17 t ha^{-1}) treatments. Significantly lowest yield was measured in the NT treatment (5.29 t ha^{-1}). Similar results were reported by Jug et al. (2013) in an experiment where the yields did not differ statistically from each other when tilled with a chisel (5.76 t ha^{-1}), ploughing (5.62 t ha^{-1}) and disc harrowing (5.59 t ha^{-1}). The lowest yield (5.40 t ha^{-1}) was achieved with the direct sowing system.

No statistically significant differences were detected for moisture content. The average humidity varied between 15.8% and 16%. The moisture content was slightly higher than is usual in agricultural practice during harvesting due to the harvesting of samples in the early morning.

Table 4. The influence of tillage systems on the yield and quality parameters of winter wheat

Soil tillage	Yield of grain 86 % DM (t ha^{-1})	Humidity (%)	Protein (%)	Hectolitre weights (kg hl^{-1})	Sedimentation
CT	6,50 ± 0,19^{a}	16,0 ± 0,11	13,4 ±0,03^{b}	73,5 ± 0,17^{bc}	53,8 ± 0,63^{b}
TC	6,17 ± 0,32^{a}	15,7 ± 0,07	13,0 ± 0,05^{c}	74,5 ± 0,37^{a}	51,5 ± 0,65^{b}
DH	6,54 ± 0,46^{a}	15,7 ± 0,07	13,6 ± 0,04^{a}	72,8 ± 0,15^{c}	56,5 ± 0,29^{a}
NT	5,29 ± 0,15^{b}	16 ± 0,11	13,1 ± 0,09^{c}	74,1 ± 0,13^{ab}	52,5 ± 0,87^{b}

^{a,b,c} significant difference (Duncan α = 0,05).

Significantly highest percentage of protein in the grain was determined at DH (13.6%) and CT (13.4%) in comparison to NT (13.1%) and TC tillage (13.0%), respectively. Regardless the differences in the amount of protein in the wheat crop, the wheat grains of all tillage treatments would be classified as B1 purchase quality class. Hectolitre weight was relatively low in all treatments, due to the large amount of precipitation at the time of harvest. In TC, a characteristically higher hectolitre weight (74.5 kg hl^{-1}) was determined compared to DH (72.8 kg hl^{-1}). The value of sedimentation was significantly higher at the DH (56.5) than in CT (53.8), NT (52.5) and TC (51.5), respectively. Based on the results of the experiment in 2022/2023, it is estimated that with the DH and TC, the same high and high-quality crops as with CT could be achieved.

CONCLUSIONS

Based on the results of a one-year field experiment on lighter alluvial soils in Srednja Bistrica, replacing the ploughing of soil with a chisel or a disc harrowing in winter wheat vegetation after harvesting corn for grain can be recommended, even when a lot of organic matter (corn straw) remains on the field surface. Many farms, even smaller ones, already have machines similar to the ones we used in the experiment, which means that it is not necessary to change the machines to switch to conservation treatment. For greater certainty of the obtained results, it would be necessary to repeat the experiment in the following growing seasons.

ACKNOWLEDGEMENTS

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50. ACTUAL TASKS ON AGRICULTURAL ENGINEERING

Original scientific paper

EFFECTS OF FALLOW AND GREEN MANURE ON THE YIELD OF SOYBEAN GRAIN AND CO_2 EMISSION WITH USE REDUCED TILLAGE

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ABSTRACT

Several current European Union policies (Green Deal, Climate Act, Biodiversity Strategy 2030, Farm to Fork Strategy) aim to transform agricultural systems, with one of the objectives being to reduce greenhouse gas emissions from agriculture. In addition, the measures mentioned are intended to use the soil as a reservoir for greenhouse gas emissions, primarily carbon dioxide (CO_2). Research into the effects of fallow and green manure on the reduction of greenhouse gas emissions is intended to contribute to these goals. A one-year study was conducted that included fallow, green fallow (growing short-vegetation siderates - sowing in autumn and incorporating above-ground plant mass into the soil in spring), and soybean cultivation with and without siderates, to determine the level of different carbon dioxide emissions. The one-year study was conducted on the Dalibor Jurina's family farm in Veliki Zdenci, Bjelovar-Bilogora County, following a randomized block design on plots of 10 x 35 m in four replicates. The treatments included in the study were as follows: I. fallow; II. fallow + green manure; III. soybean and IV. soybean + green manure. The highest C-CO_2 emissions were found in the fallow treatment. The most effective treatment for reducing C-CO_2 emissions was soybean with green manure. Soybean seed yield was also higher in the green manure treatment.

Key words: *fallow, green manure, reduced tillage, soybean yield, flux of carbon dioxide*

INTRODUCTION

Of the many greenhouse gases, carbon dioxide is an important compound that influences the process of global warming and is considered a key driver of global climate change (Lee et al., 2021). With increasing demands on agricultural production to meet the needs of a growing population, the role of agricultural practices and their impact on soil, climate, gas emissions, water resources, biodiversity, and related factors need to be considered more thoroughly than ever before (Vleeshouwers and Verhagen, 2002). Soil, as a potential carbon sink, plays a crucial role in adressing climate change. It is the second largest carbon reservoir, containing twice as much carbon as the atmosphere, and three times as much as vegetation. Moreover, soil serves as a vital sink for atmospheric CO_2 (Lal, 2004). Reducing CO_2 emissions by sequestering carbon in the soil is of paramount importance, as agricultural practices can sequester atmospheric carbon and thus mitigate climate change by maintaining and/or increasing the amount of carbon stored in soil and plant material (Rastogi et al., 2002).

Excessive tillage, the burning of crop residues, the application of large amounts of fertilizers, or alterations in the soil-air-water ratio lead to increased CO_2 emissions to the atmosphere and a reduction in the carbon content in the soil (Wang et al., 2024). Research has demonstrated that factors such as agrotechnical measures, agroclimatic factors, physical, chemical and biological properties of the soil, the presence and type of vegetation, and numerous other factors significantly influence CO_2 emissions in/from the soil (Raich and Potter, 1995; Rochete and Angers, 1999).

Tillage, in particular, has a major influence on soil CO_2 emissions (Bilandzija et al., 2016). It can lead to a loss of approximately 50% of organic carbon due to the stimulation of aerobic microbial respiration processes (Zhang et al., 2024). The presence of vegetation also influences soil CO_2 emissions, which tend to be higher in cultivated soils than in fallow soils (Al-Kaisi and Yin, 2005). Moreover, soil CO_2 emissions are also influenced by the type and phenological stage of crops, as they absorb CO_2 from the atmosphere through photosynthesis (Norman et al., 1997). Seasonal variations in soil CO_2 emissions have been observed in almost all types of ecosystems. Soil respiration is typically highest in summer, decreases during colder months, and is lowest in winter (Rochette and Angers, 1999). Seasonal variations are primarily influenced by changes in soil and air temperature, soil water content, photosynthetic activity, and/or their interactions. In spring, soil temperature and water content are not limiting factors, enabling better crop growth and increased soil respiration (Ma et al., 2024). However, in summer, soil water content becomes a limiting factor, while in winter, low soil temperatures restrict crop growth and soil respiration (Bobrenko et al., 2024).

The aim of this study was to assess CO_2 emissions from soil under different land-use practices, specifically through the cultivation of agricultural crops (in this case soybean) with or without green manure. The aim of the was to determine the soil's ability to store CO_2, one of the main sources of greenhouse gas emissions.

MATERIALS AND METHODS

Experimental site and land use

Multi-year research was conducted on the Dalibor Jurina family farm (MIBPG 191693) in Veliki Zdenci, Bjelovar-Bilogora County, (N 45˚ 65', 17˚ 08' E) according to a randomized block design on plots measuring 10 x 35 m in four replicates. This paper presents the results for the year 2022, when soybean was cultivated on the experimental field. The soil type at the experimental site is classified as Stagnic Luvisols (IUSS Working group WRB, 2022). In the following text, the researched treatments will be labeled as follows: 1. fallow; 2. fallow +

green manure; 3. soybean and 4. soybean + greeen manure. The green manure (siderate) used in this study consisted of fodder pea (*Pisum sativum* subsp. Arvense), and winter oats (*Avena sativa*). During the research, reduced tillage was uniformly applied, on the experiment, i.e. a rotary cultivator as a flat cultivator and a rotary harrow with a packer roller. It is important to emphasize that mineral fertilizers were not applied in these studies; however, the usual conventional chemical protection for the cultivated crop – soybean – was implemented. Due to extremely unfavorable climatic conditions, including a highly irregular distribution of precipitation (with an extremely rainy April and the first half of May), soybean was sown only on May 22 (variety Os Lucija 00) with a sowing rate of 130 kg ha^{-1}. The soybean harvest took place on October 8, 2022.

Calculation of carbon dioxide emissions

The field measurements of carbon dioxide concentration were carried out using the static chamber method. The measurements were carried out in triplicate at each defined research point. The carbon dioxide concentration in the soil was measured with a portable infrared carbon dioxide detector (GasAlerMicro5 IR). The material used to construct the chambers does not transmit light, thereby preventing sunlight from influencing the measurements. The chambers were placed on circular frames that were embedded approximately 5 cm into the soil. Before closing the chambers, the initial carbon dioxide on the soil surface was measured. After closing the chambers, the incubation time was 30 minutes, followed by the measurement of the carbon dioxide concentration in the closed chambers. If necessary, the vegetation inside the frame was removed before starting the measurements.

The soil carbon dioxide emission of the soil is expressed in kg ha^{-1} day^{-1}. The calculation of CO_2 emissions (flux) from the soil was performed according to Widen and Lindroth (2003) and Toth et al., (2005) using the following equation:

$$F_{CO2} = [M * p * V * (c_2 – c_1)] / [R * T * A * (t_2 – t_1)]$$

In which:

FCO_2 – flux of CO_2 from the soil (kg ha^{-1} day^{-1})
M – molar mass of CO_2 (kg mol^{-1})
p – air pressure (Pa)
V – chamber volume (m^3)
c1 – CO_2 concentration at the beginning of the measurement (µmol mol^{-1})
c2 – CO_2 concentration at the end of the measurement (µmol mol^{-1})
R – gas constant (J mol^{-1} K^{-1})
T – air temperature (K)
A – chamber area (m^2)
t2 – t1 – time of measurement – incubation (day)

Determination of agroecological conditions in soil and air

The research objective required reliable data on agro-ecological conditions, especially regarding temperature, pressure, and relative air humidity, as well as soil temperature and moisture content. Precipitation and air temperature affect the soil moisture content and soil temperature, which ultimately indirectly influence carbon dioxide emissions from the soil. At each location, air temperature was measured, along with relative humidity, air pressure, and carbon dioxide concentration in the air. In addition to these air parameters, the soil temperature and the soil moisture content were also measured. The air temperature and relative humidity were recorded with a Testo 610 device, while the air pressure was measured with a Testo 511 device positioned at a height of approximately 1 m above the soil surface. Soil temperature and moisture content were determined using an IMKO HD2 device (Trime – Pico64 probe). Before the start and at the end of the measurement of the CO_2 concentration in the soil, the following parameters were recorded: CO_2 concentration in the air (ppm), air temperature (°C), air pressure (hPa), and relative humidity of the air (%). Simultaneously, with each measurement of soil CO_2 emissions, soil temperature (°C) and soil moisture content (%) were measured at a depth of 10 cm near the chambers (Figure 1).

Figure 1. Application of the IMKO HD2 device on the experimental field in Veliki Zdenci

Data analysis

Statistical data were processed using the analysis of variance (ANOVA) method using the statistical program Statistica 14.3 and mean values were separated at the $p < 0.05$ level using the Fisher's Least Significant Difference (LSD) test.

RESULTS AND DISCUSSION

Climatic conditions during the research year

Compared to the 30-year average of 863 mm (Kisic et al., 2017), the year 2022 was at the level of the multi-year average of 892 mm precipitation. As shown in Figure 2, a lack of plant-available water was observed from May to August. During this period, a total of 199 mm of precipitation was recorded, while September saw 286 mm of precipitation over 19 days. Regarding temperature, both the monthly and annual averages for 2022 were higher than the average (Figure 3). The multi-year average is 10.7 degrees Celsius, while an average of 12.7 ˚C was recorded in 2022. Notably, during the period of greatest precipitation deficit (May-August), the highest temperatures were recorded, consistently 3.0-3.5 degrees Celsius higher than the multi-year average. This trend indicates that more extreme climate conditions could occur in the future. Dugan et al. (2024) discuss strategies for addressing the challenges posed by increasing climate variability.

Soybean seed grain yield

The distribution of precipitation with extreme amplitudes and extremely high temperatures during the late spring and summer months was the decisive factor influencing the soybean yields achieved this year. The lack of precipitation between May and August certainly had a significant impact on the soybean yields achieved this year. In addition, the extremely unfavorable conditions (excessive humidity) during the soybean sowing likely affected the crop composition, and consequently the soybean grain yield. Although a slightly higher soybean grain yield was recorded in the treatment (soybean + siderate), the differences in yields were not statistically significant. The lack of precipitation in October had no significant effect on the soybean yield, since harvesting was carried out on October 8. In conclusion, it can be said that the climatic factors, in particular the unfavorable distribution of precipitation and extremely high summer temperatures, were the decisive influences on the achieved yield of the cultivated crop (Figure 4). The effect of the climatic factors masked the impact of the green fertilization. One potential response to the challenges of climate change is the application of various forms of reduced tillage (Đekemeti et al., 2019).

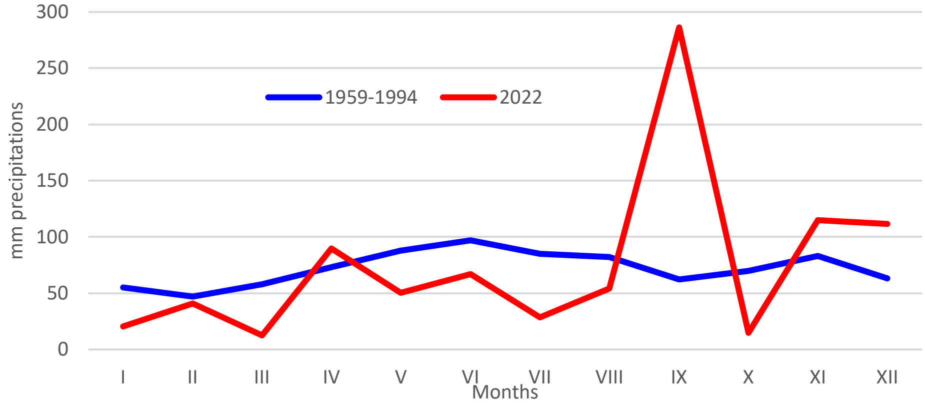

Figure 2. Total monthly precipitation in the research year and multi-year average

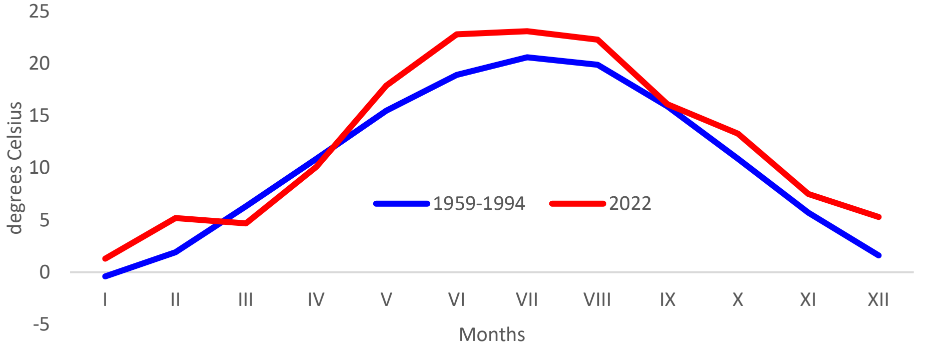

Figure 3. Mean monthly temperatures in the research year and multi-year average

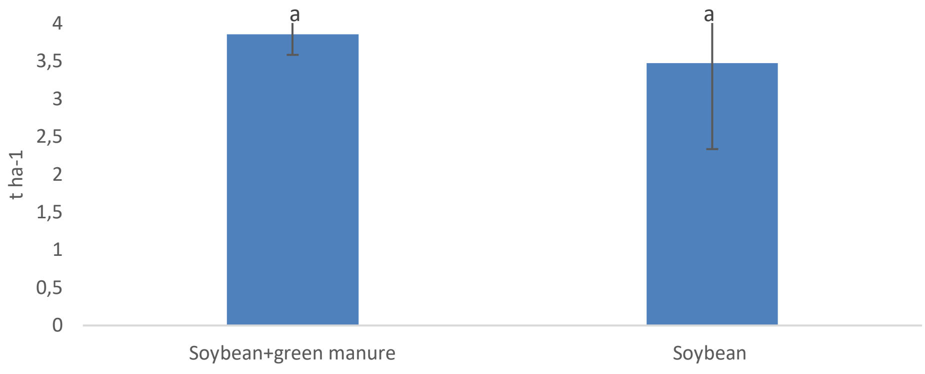

Figure 4. Achieved yields of soybean seeds
Mean values marked with the same letters between the achieved yields of soybean seeds are not statistically significantly different (Statistica 14.3, $p < 0.05$)

Soil microclimate conditions

The results related to soil temperature and moisture show significant differences during the three measurements of C-CO_2 emissions (Table 1). In the first measurement of soil temperature in June, the fallow treatment had a significantly higher soil temperature. In July, both fallow+green manure and soybean treatments had significantly higher temperatures than the other two treatments. In the last measurement, immediately before the soybean harvest, fallow and fallow+green manure had significantly lower temperatures compared to soybean and soybean+green manure. The same table also shows the soil moisture in the investigated treatments. In the first measurement in June, there were no significant differences in soil moisture between the different treatments. In July, differences appeared, and significant differences were found between the treatments with green manure and without green manure. A similar situation was recorded in the last measurement in October, when no differences were registered between the treatments of soybean with green manure and soybean without green manure. However, significant differences were determined between fallow and soybean.

Table 1. Soil microclimate by different land use or crops

Date of measurement	Fallow	Fallow+green manure	Soybean	Soybean+green manure
		Soil temperature, °C		
June 15, 2022	39.82 a	35.57 d	36.61 b	36.02 c
July 22, 2022	34.53 a	36.73 b	36.53 b	35.21 c
October 5, 2022	21.28 a	21.18 a	23.55 b	25.55 c
		Soil moisture, %		
June 15, 2022	23.92 a	22.63 a	21.37 a	22.43 a
July 22, 2022	6.89 a	4.24 ab	8.46 ac	6.91 a
October 5, 2022	55.65 a	59.69 b	63.93 c	61,21 b

Mean values marked with the same letters between the achieved yields of soybean seeds are not statistically significantly different (Statistica 14.3, $p < 0.05$)

Soil emissions C-CO_2

Carbon dioxide is released from the soil by soil respiration, which includes three biological processes: biological respiration, root respiration, and soil micro- and macrofaunal respiration (Rastogi et al., 2002). Of all greenhouse gases, carbon dioxide is extremely important, as it causes about 60% of global warming (Vleeshouwers and Verhagen, 2002). For these reasons, research is being conducted on how to store as much carbon dioxide as possible in the soil. There are several methods, primarily focused on changing soil cultivation practices, i.e. increasing the use of reduced tillage methods (Wang et al., 2024) or adopting a wider crop rotation (Zhang et al., 2024). Also, a change in land use (reducing arable land) and increasing land under meadows and pastures will enhance the potential for carbon storage in the soil. Regardless of the processing method applied or crop rotation, current weather conditions have the greatest influence on carbon dioxide emissions from the soil (Norman et al., 1997; Wang et al., 2024).

Figure 5 shows the C-CO_2 emission approximately 20 days after sowing soybeans. As expected, the highest C-CO_2 emission, significantly higher than the other treatments, was recorded in the classic fallow. The emission was significantly higher in the fallow+green manure treatments compared to the soybean treatments, and significantly lower in the classic fallow. The treatments where soybeans were grown had significantly lower C-CO_2 emissions compared to the two fallow plots. No significant differences were found between the soybean treatments (with and without green manure). Similar results were found by other researchers. Rochette and Angers (1999) and Sokolova et al. (2021) reported the highest C-CO_2 emissions during the spring months on fallow plots.

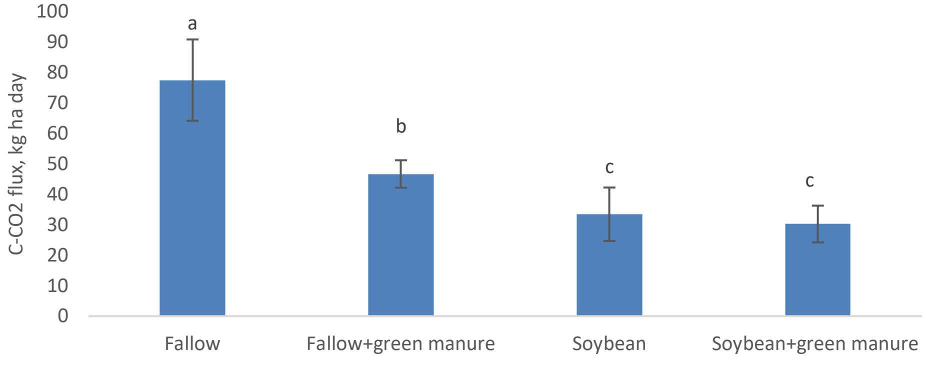

Figure 5. Soil C-CO_2 emissions on June 15
Mean values marked with the same letters between the achieved yields of soybean seeds are not statistically significantly different (Statistica 14.3, $p < 0.05$)

The next measurement of C-CO_2 emissions was conducted on July 22. In this measurement, the significantly highest C-CO_2 emissions were recorded in the fallow+siderate treatment compared to the classic fallow and soybean without siderate. The treatment in which soybeans were grown without siderate recorded the significantly lowest C-CO_2 emissions compared to the other three treatments.

The last measurement of C-CO_2 emissions was carried out on October 5, three days before the soybean harvest. The significantly highest C-CO_2 emissions were measured in the fallow compared to the other three treatments. In addition, the significantly lowest C-CO_2 emission was measured soybean+green manure treatment compared to the other three treatments. No significant differences were recorded between the fallow+green manure treatment and soybean without green manure.

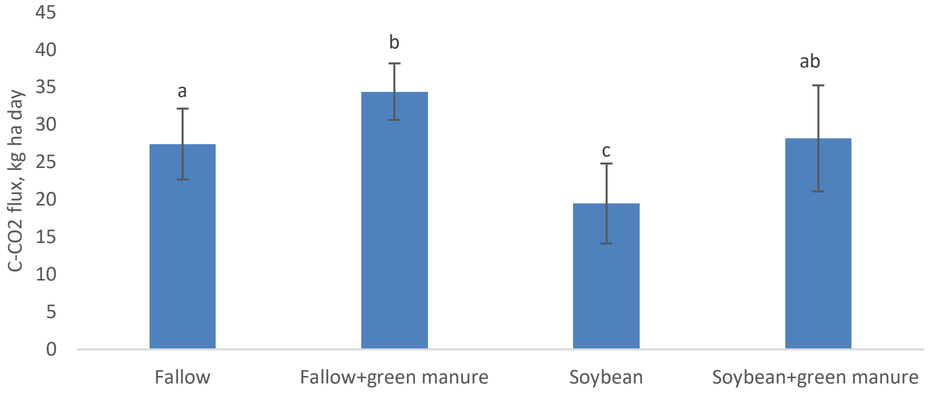

Figure 6. Soil C-CO_2 emissions on July 22
Mean values marked with the same letters between the achieved yields of soybean seeds are not statistically significantly different (Statistica 14.3, $p < 0.05$)

Figure 7. Soil C-CO_2 emissions on October 5
Mean values marked with the same letters between the achieved yields of soybean seeds are not statistically significantly different (Statistica 14.3, $p < 0.05$)

Based on the research results and the literature review, it is evident that carbon dioxide emissions from the soil vary significantly depending on plant cover and meteorological conditions throughout the year. Further research is essential to identify changes in physical and chemical properties and to evaluate the impact of green manure on these properties, as well as on the yield of cultivated crops.

CONCLUSIONS

Based on the one-year research conducted, the following conclusions can be drawn:

- No significant differences were recorded between the treatments in which soybeans were grown. The extremely dry year in the growing season and the very unfavourable distribution of precipitation indicate that the climatic (un)conditions had a decisive influence on the achieved soybean grain yield.
- The treatment involving classical fallow recorded the highest C-CO_2 emissions, followed by the fallow treatment with green manure.
- The most favourable treatment in terms of reducing C-CO_2 emissions was fallow with soybeans, i.e. soybean cultivation.

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50. ACTUAL TASKS ON AGRICULTURAL ENGINEERING

Preliminary communication

INFLUENCE OF DIFFERENT CORN HYBRIDS ON SOIL RESPIRATION AND MICROCLIMATE

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ABSTRACT

Soil respiration is an important component of the global carbon cycle and is linked to the global problem of climate change caused by increasing greenhouse gas (GHG) concentrations in the atmosphere. Land use has an influence on soil respiration rates. The aim of the study is therefore to determine the influence of the cultivation of 4 different corn hybrids on the soil respiration rate and soil microclimate (temperature and moisture). The study was conducted in the 2021 growing season in the continental part of Croatia near the city of Osijek. The experiment included 5 treatments (bare soil, Rudolfov, Kulak, OS 515, OS 596). Soil respiration increased with plant developmental stages until maturity and then decreased until harvest. The average soil respiration rates in vegetation period May – October were in the range of 0.82 - 2.15 t C-CO_2 ha^{-1}, soil moisture 23.71 - 27.26 % and soil temperature 27.63 - 28.15 °C depending on studied treatment. Significant differences were not found for the average values of soil respiration rates and soil microclimate conditions between corn hybrids, but soil respiration rates were significantly higher (2.37 times) at the treatments with corn presence compared to the bare soil indicating significant impact of vegetation on soil respiration.

***Keywords**: soil CO_2 efflux, soil temperature, soil moisture, corn hybrids, climate change*

INTRODUCTION

Climate change is one of the greatest environmental problems nowadays. Croatia is already facing the impacts of climate change, as annual temperature trends are positive and significant for all parts of Croatia and statistically significant decreases in precipitation were found for some Croatian regions (NIR, 2021). According to local and global climate changes scenarios for the near future, further climate changes and more frequent extreme weather conditions for Croatia are expected (Marinović et al., 2021). A climate change is caused by anthropogenic emissions of greenhouse gases into the atmosphere. The concentration of carbon dioxide (CO_2) in the atmosphere at the beginning of the 20th century was around 380 ppm (Feely et al., 2004), and in 2021 the CO_2 concentration reached 414 ppm (Friedlingstein et al., 2022). For this reason, intensive efforts are being made to find ways of reducing greenhouse gas emissions into the atmosphere and increasing the atmospheric carbon sink. The carbon cycle represents the biochemical cycle of carbon exchange between the atmosphere, hydrosphere, biosphere and lithosphere and is a consequence of biological, chemical, physical and geological processes. As a potential carbon sink, soil can be a key factor in tackling climate change, as it contains twice as much carbon as the atmosphere and three times as much carbon as vegetation (Bilandžija et al., 2016).

Soil respiration is the process where one part of photosynthesis-sequestered C is returned from the soil back to the atmosphere. The release of CO_2 from soils accounts for about 25% of the total annual exchange of C between the atmosphere and terrestrial sources (Post et al., 1990), and is estimated to be 75 Pg C (Schlesinger and Andrews, 2000). Therefore, understanding the factors that control soil respiration is of particular importance to land use and management, since certain measures can be taken to enable lands to sequester more atmospheric C and decrease soil respiration (Townsend et al., 1996; Nadelhoffer et al., 1999; Bowden et al., 2004). There are lot of possibilities to mitigate climate change via decreasing soil respiration in agricultural sector through implementation of new technologies and sustainable agricultural practices (Bilandžija et al., 2016; Bilandžija et al., 2021). One of these technologies is agricultural biotechnology, a promising tool for development of cultivars and hybrides that can contribute to mitigation of climate change (McCarthy et al., 2018). Therefore, the aim of the study is to determine the impact of four different corn hybrides on soil respiration rates and soil microclimate conditions (soil temperature and soil moisture content).

MATERIALS AND METHODS

Experimental site

A study on soil respiration was conducted in 2021 at a experimental site near the city of Osijek (45°31'55.6 "N, 18°44'13.8 "E, 90 m a.s.l.). According to the multi-year average 1991 – 2018, the Osijek region has a continental climate with an average annual air temperature of 11.7 °C, an average annual precipitation amount of 707 mm, an evapotranspiration of 590 mm per year, a soil water deficit in the period July - September (72 mm) and a water surplus in the period December - March (116 mm) (Bilandžija i Martinčić, 2021). The soil at the experimental site has a silty clay texture, the water holding capacity is 37.7%, the air holding capacity is 10.2%, the soil porosity is 47.8% and the bulk density is 1.39 g cm^{-3}. The pH_{KCl}

value of the soil is 7.24, the soil contains 2.3% humus, 0.11% total nitrogen, 1.25% total carbon, 0.06% total sulphur, 17.9 mg P_2O_5 and 15.5 mg K_2O per 100 g soil.

Experimental treatments

The experiment includes five different treatments with control plot and different corn hybrides. The size of each experimental plot is 150 m^2 (15 m x 10 m) in three repetitions. Description of corn hybrids is presented in Table 1, and more informations on corn hybrides can be found in Catalouge of Agricultural Institute Osijek (AIO, 2020). The experimental treatments are:

1) C – control plot, bare soil - black fallow
2) R - corn (*Zea mays* L.), hybride Rudolfov 60
3) K - corn (*Zea mays* L.), hybride Kulak
4) 515 - corn (*Zea mays* L.), hybride OS 515
5) 596 – corn (*Zea mays* L.), hybride OS 596

Table 1. Description of corn hibrides

	RUDOLFOV	**KULAK**	**OS 596**	**OS 515**
Purpose	dry grain production, ear harvesting, silage production		ear harvesting, silage production	silage production
Kernel type	Dent-type kernel			
Number of rows of kernels	16 – 18		14 – 16	16 – 18
Recommended plant density	68 000 – 71 000 germinable seeds/ha, 39 000 – 41 000 germinable seeds/cadastral	71 000 – 75 000 germinable seeds/ha, 41 000 – 44 000 germinable seeds/cadastral	65 000 – 68 000 germinable seeds/ha, 38 000 – 39 000 germinable seeds/cadastral	68 000 – 71 000 germinable seeds/ha, 39 000 – 41 000 germinable seeds/cadastral
Sowing distance	20 – 21 cm	19 – 20 cm	21 – 22 cm	20 – 21 cm

Source: Agricultural Institute Osijek (2020)

Soil respiration

Field measurements of soil CO_2 concentrations, air (temperature, pressure and relative humidity) and soil (temperature and moisture at 10 cm depth) climate elements were conducted once a month during the growing season (May – October) in three repetitions. The total number of measurements amounted 105 (7 months x 5 treatments x 3 repetitions). The measurement of air temperature and relative air humidity was carried out with Testo 610 (2011), air pressure with Testo 511 (2011) at the height of 0.5 m above soil surface, soil temperature and soil moisture at 10 cm depth with IMKO HD2 (2011), in the close vicinity of each chamber. Soil CO_2 concentrations were measured by *in situ* closed static chamber method and portable infrared detector of carbon dioxide (GasAlerMicro5IR, 2011). The soil respiration rates were afterwards calculated as:

$$F_{CO2} = \frac{M \times p \times V \times (c_2 - c_1)}{R \times T \times A \times (t_2 - t_1)} \quad (1)$$

where:

FCO_2 – soil respiration (kg ha^{-1} day^{-1});
M – molar mass of the CO_2 (kg mol^{-1});
P – air pressure (Pa);
V – chamber volume (m^3);
c_1 – initial concentration of CO_2 (µmol mol^{-1});
c_2 – concentration of CO_2 after incubation time (µmol mol^{-1});
R – gas constant (J mol^{-1} K^{-1});
T – air temperature (K);
A – chamber surface (m^2);
t_2 - t_1 – incubation period (day).

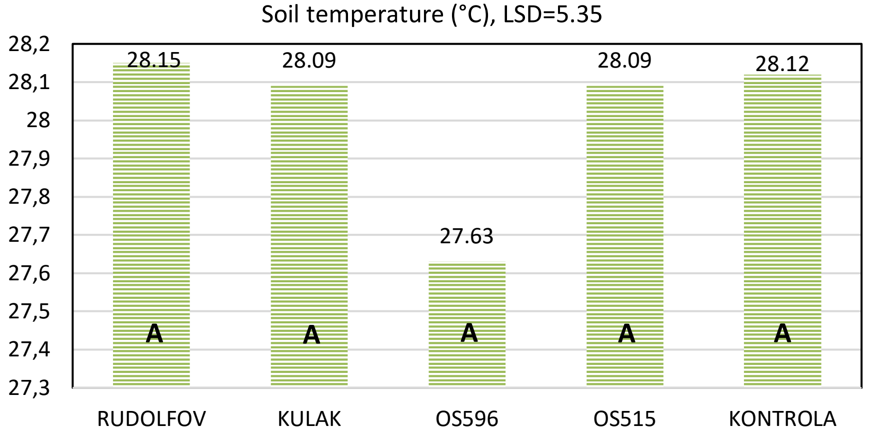
Statistical analysis

All data were analyzed using statistical Software SAS (SAS 9.4, SAS Institute Inc.). Variability between treatments were evaluated with analysis of variance (ANOVA) and tested, if it was necessary, with adequate post-hoc (Fisher LSD) t-test. In all statistical tests significance level was 5%.

RESULTS AND DISCUSSION

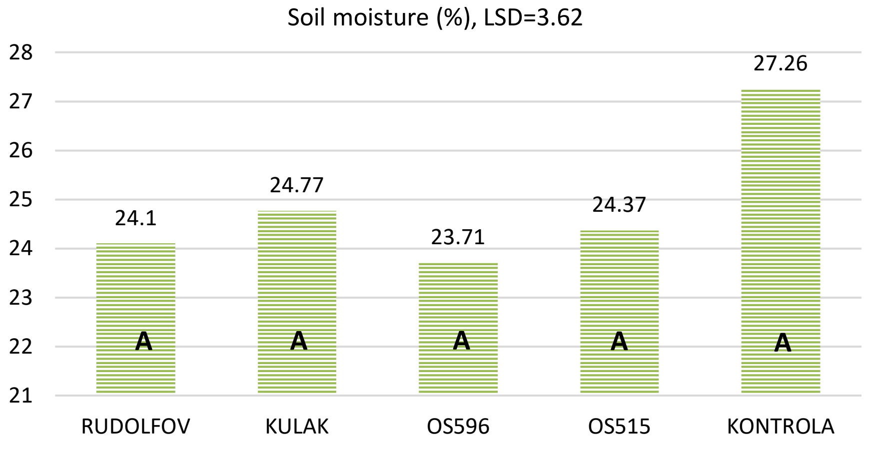
Results

Soil temperature during the studied period was in the range of 12.4 - 39.5 °C with an average value of 28.02±7.89 °C. Statistical analyses determined no significant differences in soil temperature between studied treatments (Graph 1).



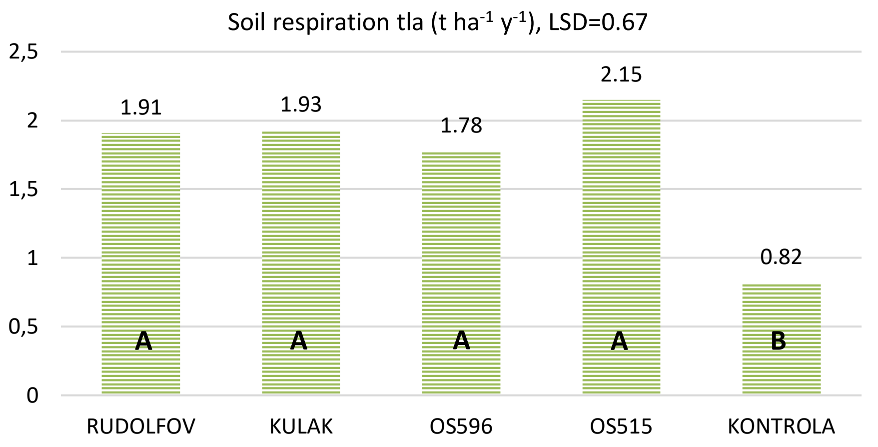
Graph 1. Average soil temperature during the studied period May - October

During the studied period soil moisture was in the range of 12.14 - 35.89 % with an average value of 24.84±5.48 %. No statistically significant differences between studied treatments was determined for soil moisture content (Graph 2).



Garph 2. Average soil moisture content during the studied period May - October

Soil respiration rates during the vegetation period May - October were in the range of 0.6 - 3.69 t ha^{-1} y^{-1} with an average value of 1.71±0.7 %. Average soil respiration rates of Rodolfov, Kulak, OS596 and OS515 during the studied period do not differ statistically between themselfs and amounts 1.91, 1.93, 1.78 and 2.15 t ha^{-1}y^{-1}, respectively (Graph 3). Statistically significant difference was determined between treatments with corn hybrides and black fallow. Average soil respiration rate of 4 studied hybrides amounts 1.94 t ha-1y-1 and is on average 2.37 times greater compared to soil respiration rate of black fallow (Graph 3).



Garph 3. Average soil respiration rates during the studied period May - October

The amount of carbon released from the soil to the atmosphere by soil respiration processes in this study correlates with the values determined by Ding et al. (2007), who found that the soil respiration rate of bare soil - black fallow amounts 0.80 t ha^{-1} and on the field with corn presence 1.63 t C ha^{-1} i.e. soil respiration in the field with corn is 2 times greater than soil respiration in a field with black fallow. The study on the effects of fertilization on soil respiration under corn in continental Croatia near Sisak city, reveal that soil respiration was 1.8 to 2.1 times lower on bare soil compared to treatments with corn (Galić et al., 2023) that ranged from 2.65 to 2.98 t C ha^{-1} depending on the treatment. In a study conducted near Daruvar city in continental Croatia on the influence of different tillage methods on the soil respiration rate was found that the average soil respiration under maize is 3.1 t C ha^{-1} during the growing season, which is higher than the values determined in this study (Bilandžija et al., 2016). Ussiri and Lal (2009) determined an average soil respiration rate of 19.4 kg C ha^{-1} day^{-1} for corn cultivation in Ohio, which corresponds to 3.57 t C ha^{-1} for the growing season May - October. These values are higher than the results obtained in this study, which is attributed to the different agro-ecological conditions and the agrotechnical measures applied.

CONCLUSION

In this study, the degree of soil respiration and soil microclimate conditions were determined for four different maize hybrids (Rudolfov, Kulak, OS596 and OS515) and bare soil. The statistical analysis of variance showed that soil respiration did not differ significantly between the maize hybrids studied. However, it was found that soil respiration was 2.37 times higher in treatments with plant cover than in bare soil. To determine the possibility of mitigating climate change through the cultivation of different hybrids, it is necessary to extend research to the potential of biological carbon sequestration and the determination of the total carbon balance within a given agroecosystem

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50. ACTUAL TASKS ON AGRICULTURAL ENGINEERING

Original scientific paper

ENERGY CONSUMPTION AND GHG EMISSIONS IN MAIZE-CEREALS INTERCROPPED CULTIVATION DURING ARID VEGETATIVE PERIOD

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ABSTRACT

Combinations of maize and intercrops can improve the efficiency of energy use and prevent high GHG emissions due to expected higher yields from area units and better energy use ratio. In Lithuania, due to climate change, some vegetative periods became arid with about 50-60% of the usual precipitation rate. In such conditions, the intercrops are sown after emergence of maize encounter with unfavorable germination and development conditions, and this can decrease the biomass yields of intercrops. That disbalance energy use of intercropped cultivations.

For more precise conclusions, investigations were performed at the Experimental Station of Vytautas Magnus University, Lithuania. Maize was intercropped with Poaceae family crops as more stable for arid conditions than legumes: winter ray, spring barley, annual ryegrass, oats. Control treatments were two: inter-rows weeding and inter-row mulching with weeds. The operations of maize intercropping increased fuel consumption by about 10 l ha^{-1} compared to the control without any intercrops. When growing maize with cereal intercrops, the total energy consumption increased by almost 50% compared to the control.

Less pollution was established by two agro-technologies without intercrops. The environmental pollution was also low by the sowing of annual ryegrass because its seeding rate was low. When sowing large-sized seed crops into maize, CO_2 equivalent is higher and such technologies are relatively more polluting.

***Keywords**: CO_2 equivalent, drought, energy, multi-crops*

INTRODUCTION

In agriculture, oxygen is released during production, but also a significant amount of GHG, which pollutes the environment (Lal, 2004; Faila et al., 2020; Saldukaitė et al., 2022). There are various methods of reducing environmental pollution by GHG in agriculture, such as: balancing organic and mineral crop fertilization, application of reduced tillage. Also important are their combinations (Haddaway et al., 2017; Bručienė et al., 2021). This provides prerequisites for more efficient fuel and energy consumption, as well as a relatively lower CO_2 equivalent emitted into the atmosphere. Multi-cropping can be an effective way to reduce energy consumption and balancing GHG emissions. Multi-crops can also stabilize soil and crops fertility due to control of pests, diseases and weeds, especially in sensitive conditions of climate change (Haberl et al., 2011; De Cárcer et al., 2019; Blanco-Canqui and Ruis, 2020). In agriculture, it is useful to convert various inputs into equivalents of energy consumption and carbon emissions. So, there is a need for a standardized approach to quantify those indices in any conventional and innovative agro-technology (Trimpler et al., 2016).

The main aim of this study was to evaluate the fuel and energy consumption, and GHG emissions from maize cultivation, intercropped by the *Poaceae* intercrops in conditions of not well distributed annual precipitation.

MATERIAL AND METHODS

Field short-term experiment on maize intercropping was performed since 2023 at the Experimental station of Vytautas Magnus University, Agriculture Academy. Experimental soil was sandy loam (sand 57.4%, clay 14.9%) Planosol (WRB, 2014). Lithuania is a country with surplus precipitation rates, but last few years precipitation rates distribute not even with drought periods during vegetative period (Table 1).

Spring 2024 was not cool and dry, but rather warmer and wetter. The summer months were exceptionally warmer than normal. Only July was getting wetter. All others are exceptionally dry, so the growth of intercrops canopy biomass was weak. In 2023, 250 mm of rain fell during the maize vegetation, and in 2024 - about 280 mm. This amount of precipitation is sufficient for maize cultivation, but in our climate, the fields are impoverished and do not produce a larger biomass yield.

In our study, 6 treatments were evaluated: 1. Inter–row loosening (control 1, C1); 2. Inter–row mulching with weeds (control 2, C2); 3. Winter ray intercropped (WR); 4. Annual ryegrass intercropped (AR); 5. Spring barley intercropped (SB); 6. Oats intercropped (OA).

The field experiment was carried out in 4 replicates. Crops were grown as continued cultivation. The soil was ploughed with a Kverneland semi-screw plough in autumn. In the spring, the soil was cultivated by cultivator by the 4.3—4 cm depth. At the same time mineral fertilizers NPK 5:15:29 (300 kg ha^{-1}) were applied. After, the maize was sown with a Kverneland Accord Optima pneumo-mechanical seeding machine in 45 cm wide rows at the rate 30-32 kg ha^{-1} of seeds. After the maize germinated, the inter-rows were cultivated and inter-row *Poaceae* crops were inter-sowed. Sowing rate for ray and barley – 200 kg ha^{-1}, for outs – 220 kg ha^{-1}. Pesticides were not used in agro-technologies. The biomass was harvested at the end of the maize vegetative period at the end of September (after the grain has reached the beginning of hard maturity) manually.

Table 1. Air temperatures and precipitation rates during maize vegetative period (Source: Kaunas Meteorological Station, 2024)

Month s	10-days periods			Monthly	Long-term average
	I	II	III		
Air temperature (°C)					
IV	11.1	7.6	8.1	9.1	6.9
V	12.9	14.0	19.8	15.6	13.2
VI	16.5	16.8	20.1	17.8	16.1
VII	19.2	21.6	9.4	20.1	18.7
VIII	19.0	19.8	20.1	19.7	17.3
IX	19.5	17.8	14.5	17.3	12.6
Precipitation rate (mm)					
IV	10.3	23.9	28.8	63.0	41.3
V	7.2	4.6	13.3	25.1	61.7
VI	9.9	10.4	16.5	36.8	76.9
VII	6.6	38.8	64.0	109.4	96.6
VIII	19.5	11.0	10.4	40.9	88.9
IX	0.7	31.3	8.2	52.6	60.0

In the calculations of the energy and environmental assessment of agro-technologies, there was used the normative data of the Lithuanian Institute of Economy and Rural Development for agricultural machinery (Srebutėnienė, 2017; Srebutėnienė and Stalgienė, 2017). A field area of 2–10 ha for the calculations was used. The power of tractors varied from 45 to 102 kW, biomass harvester - 250 kW (Table 2). The data of mechanical seeders are presented in calculations when up to 200 kg ha^{-1} seeds were sown.

Table 2. Agro-technological operations

Technological operation (machinery/depth/material rate)/Treatments	C1	C2	WR	AR	SB	OA
Deep ploughing	+	+	+	+	+	+
Pre-sowing cultivation	+	+	+	+	+	+
Fertilization (N_{15} P_{45} K_{87} kg ha^{-1})	+	+	+	+	+	+
Maize sowing	+	+	+	+	+	+
Intercrops sowing	-	-	+	+	+	+
Inter-row loosening (2–3 cm depth)	++	+	+	+	+	+
Inter-row mulching	-	+	+	+	+	+
Biomass harvesting	+	+	+	+	+	+

Notes: 1. Inter–row loosening (control 1, C1); 2. Inter–row mulching with weeds (control 2, C2); 3. Winter ray intercropped (WR); 4. Annual ryegrass intercropped (AR); 5. Spring barley intercropped (SB); 6. Oats intercropped (OA).

For cutting the inter-rows, the closest available hanging rotary mower was choose. In the case of a plot up to 10 ha in area, biomass yield up to 12 t ha^{-1}, and a swath width of 3 m, a 6-furrow biomass harvester was chosen. In Table 3, the main technical indicators of the technological processes, including the power of the machines, the working width, the output rate, and the cost of working time, as well as the cost of diesel fuel were presented. The highest fuel consumption is determined for harvesting operations.

Table 3. Technological indices of operations (according to the Romaneckas et al., 2024)

Technological operation	Machinery power (kW)	Working width (m)	Field capacity (ha h^{-1})	Working time (h ha^{-1})	Fuel consumption (L ha^{-1})
Deep ploughing	102	1.75	0.80	1.25	24.1
Pre-sowing cultivation	102	7.00	4.56	0.22	6.4
Maize sowing	45	3.00	1.41	0.71	4.0
Intercrops sowing	67	3.00	1.31	0.76	9.8
Fertilization	67	14.00	16.55	0.06	0.6
Inter-row loosening	54	3.00	1.56	0.64	4.1
Intercrops mulching	54	3.00	2.05	0.49	5.3
Biomass harvesting	250	3.00	1.82	0.55	19.2

General fuel consumption in C1 agro-technology was 62.5 l ha^{-1}, C2 – 63.7 l ha^{-1}, in intercropped maize – 73.5 l ha^{-1}. Seeding and interrow cutting operations increased fuel consumption by about 10 l ha^{-1}. It would be possible to sow inter-crops during maize sowing, but inter-row thinning before sowing inter-crops could be impossible. It is an effective way to control early-emerging weeds in pesticide-free technologies.

By selecting the energy equivalents of technological operations (Table 4), it is possible to evaluate the energy efficiency of different agro-technologies.

Table 4. Energy equivalents in agro-technologies

Indices	Energy equivalent	References
Human labor (MJ h^{-1})	1.96	Lal et al., 2019
Diesel fuel (MJ l^{-1})	56.3	
Agricultural machinery (MJ h^{-1})	357.2	Campiglia et al., 2020
Seeds of maize (MJ kg^{-1})	16.6	Lal et al., 2019
Seeds of ray (MJ kg^{-1})	13.8	Vinci et al., 2022
Seeds of barley (MJ kg^{-1})	14.8	
Seeds of oat (MJ kg^{-1})	15.9	
Seeds of *Poaceae* grasses (MJ kg^{-1})	18.5	Jørgensen et al., 2007
N (MJ kg^{-1})	60.6	Lal et al., 2019
P_2O_5 (MJ kg^{-1})	11.1	
K_2O (MJ kg^{-1})	6.7	

It is convenient to evaluate agro-technologies according to the relative emissions of greenhouse gases. The equivalent of CO_2 gas (CO_2eq) is used for this (Table 5).

Table 5. CO_2 equivalents in agro-technologies

Inputs	CO_2 equivalent	References
Diesel fuel (kg CO_{2eq} l^{-1})	2.76	Moghimi et al., 2014
Agricultural machinery (kg CO_{2eq} MJ^{-1})	0.071	Pishgar-Komleh et al., 2012
Seeds of maize (kg CO_{2eq} kg^{-1})	15.3	Singh et al., 1997
Seeds of cereals (kg CO_{2eq} kg^{-1})	10.2	Linquist et al., 2012
N (kg CO_{2eq} kg^{-1})	1.30	
P_2O_5 (kg CO_{2eq} kg^{-1})	0.20	Lal, 2004
K_2O (kg CO_{2eq} kg^{-1})	0.15	

RESULTS AND DISCUSSION

Energy inputs

Agriculture is an energy-intensive industry due to the use of various power machines and implements for tillage, sowing, crop maintenance and harvesting (Mohammadshirazi et al., 2012; Imran et al., 2020; Šarauskis et al., 2020). Studies have shown that a significant amount of energy is consumed in the production of mineral fertilizers and their use in agriculture. The lowest energy input was identified as human labor (Gezer et al., 2003).

Table 6. Energy inputs of technological operations

Inputs	C1	C2	WR	AR	SB	OA
Human labor	7.8	7.7	9.2	9.2	9.2	9.2
Diesel fuel	3518.8	3586.3	4138.0	4138.0	4138.0	4138.0
Agricultural machinery	1453.8	1400.2	1671.8	1671.8	1671.8	1671.8
Seed of maize (30 kg ha^{-1})	498.0	498.0	498.0	498.0	498.0	498.0
Seeds of ray (200 kg ha^{-1})	-	-	2760.0	-	-	-
Seeds of ryegrass (30 kg ha^{-1})	-	-	-	555.0	-	-
Seeds of barley (200 kg ha^{-1})	-	-	-	-	2960.0	-
Seeds of oat (220 kg ha^{-1})	-	-	-	-	-	3498.0
N	909.0	909.0	909.0	909.0	909.0	909.0
P_2O_5	499.5	499.5	499.5	499.5	499.5	499.5
K_2O	582.9	582.9	582.9	582.9	582.9	582.9
Total energy input	**7469.8**	**7483.6**	**11068.4**	**8863.4**	**11268.4**	**11806.4**

Notes: 1. Inter–row loosening (control 1, C1); 2. Inter–row mulching with weeds (control 2, C2); 3. Winter ray intercropped (WR); 4. Annual ryegrass intercropped (AR); 5. Spring barley intercropped (SB); 6. Oats intercropped (OA).

In our experiment, the lowest energy consumption was calculated in the agrotechnologies applied in control fields C1 and C2 (Table 6). When maize is grown with cereal intercrops, total energy consumption increases by about 50 percent compared to the C1 control.

Effect on the environment

Given that climate change is driven by increasing GHG due to anthropogenic impacts, sustainable farming warrants lower emissions (Whitfield, 2006; Gant et al., 2011). Optimal N fertilization level in maze-pea intercropped cultivation also can reduced GHG emissions (Yang et al., 2023).

The GHG emissions for the agrotechnological inputs were recalculated into a CO_{2eq} system using the conversion equivalents (Bosco et al., 2011) (Table 7).

Table 7. GHG emissions from maize cultivations

Indices/Treatments	C1	C2	WR	AR	SB	OA
Diesel fuel (kg CO_{2eq} ha^{-1})	172.5	175.8	202.9	202.9	202.9	202.9
Agricultural machinery (kg CO_{2eq} ha^{-1})	103.2	99.4	118.7	118.7	118.7	118.7
Seeds (kg CO_{2eq} ha^{-1})	459.0	459.0	2499.0	765.0	2499.0	2703.0
Fertilizers (kg CO_{2eq} ha^{-1})	41.6	41.6	41.6	41.6	41.6	41.6
Total GHG emission (kg CO_{2eq} ha^{-1})	**776.3**	**775.8**	**2862.2**	**1128.2**	**2862.2**	**3066.2**

Notes: 1. Inter–row loosening (control 1, C1); 2. Inter–row mulching with weeds (control 2, C2); 3. Winter ray intercropped (WR); 4. Annual ryegrass intercropped (AR); 5. Spring barley intercropped (SB); 6. Oats intercropped (OA).

The first two agrotechnologies, which did not sow intercrops, were somewhat superior in terms of CO_2 equivalent (Table 7). The environmental pollution was also low during the sowing of ryegrass because the its seeding rate was low. It is very relevant that when sowing crops, conditional emissions of greenhouse gases are high and if the sowing does not produce a tangible harvest, such technologies pollute the environment more. In our earlier study with legumes intercropping, GHG emissions varied from 803.8 to 897.8 kg CO_{2eq} ha^{-1} and were similar for all technologies (Romaneckas et al., 2024). In Silva et al. (2024) experiment under no-tillage system, maize cultivation with *Gramineae* and legume cover crops showed 0.7 and 0.1 kg CO_{2e} kg^{-1} less emissions than sole maize. In other experiments, in continue maize cultivations, fertilized at 101 kg N ha^{-1} per year, CO_2 equivalent emitted 1250 kg ha^{-1} (McSwiney et al., 2010). Juarez-Hernandez et al. (2019) found the total GHG emissions in maize cultivations up to 3475.8 kg CO_{2eq} ha^{-1}. So, agro-technologies C1, C2 and AR can be called sustainable.

CONCLUSION

The operations of maize intercropping increased fuel consumption by about 10 l ha^{-1} compared to the control C1 without any intercrops. When growing maize with cereal intercrops, the total energy consumption increased by almost 50 percent compared to the control C1.

Less pollution was the first two agro-technologies (C1 and C2), in which no intercrops were sown. The environmental pollution was also low during the sowing of annual ryegrass because its seeding rate was low. When sowing large-grain crops into maize, conditional greenhouse gas emissions are high, and if the sowing does not produce a tangible biomass yield in unfavorable vegetation conditions, such technologies are relatively more polluting.

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POSSIBILITIES OF GROWING ARUNDO DONAX ON WASTE MATERIALS

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ABSTRACT

The aim of this study was to investigate the growth of the energy crop Arundo donax (AD) on different substrates and its possible use as soil conditioner. The main objective was to determine and compare the influence of 2 different materials: (i) phosphogypsum (FG - $CaSO_4 \times 2H_2O$) and (ii) substrate (CaF_2 + municipal sewage sludge) on the total content of S, Ca, Pb, Zn, As and U in the soil, as well as yield (mass) and yield components (number of shoots and plant height). An experiment consisted of 5 different treatments (different ratios and combinations applied to the soil) in 3 replicates. The treatments were: I - soil (100 %); II - substrate (100 %); III - soil + substrate (50 % / 50 %); IV - FG + soil (50 % / 50%) and V- FG + substrate (50 % / 50%). The rhizomes of AD (~ 20 cm with 4-6 plant buds) were planted on 12/04/2023. The first harvest took place on 27/02/2024. Soil samples were taken before the establishment of the trial (2023) and after the first harvest (2024). Depending on the treatment, the pH_{KCl} value ranged from neutral 6.87 (V) to slightly alkaline 7.64 (III). The organic matter content ranged from a medium 2.2 % (I) to a highly humic 7.0 % (II). The total S content ranged from 497 $mgkg^{-1}$ (I) to 2480 $mgkg^{-1}$ (V). The Ca content ranged from 16 807 $mgkg^{-1}$ (I) to 214 225 $mgkg^{-1}$ (V), the Zn content from 99 $mgkg^{-1}$ (I) to 576 $mgkg^{-1}$ (II), the Pb content from 18 $mgkg^{-1}$ (IV) to 86 $mgkg^{-1}$ (II), the U content from 5 $mgkg^{-1}$ (I, II and III) to 111 $mgkg^{-1}$ (V) and the As content from 10 $mgkg^{-1}$ (II) to 19 $mgkg^{-1}$ (IV). The number of shoots varied from 4 per pot (I) to 8 per pot (V), the plant height from 73 cm (V) to 137 cm (I) and the fresh mass from 376 g per pot (V) to 498 g per pot (II). The Zn *content in all treatments except in clean soil (I) was above the MAC value prescribed by Croatian legislation.*

Keywords: *Energy crop, phosphogypsum, sewage sludge, municipal wastewater,* CaF_2

INTRODUCTION

Waste management and the circular economy are two interrelated concepts that promote sustainable approaches to environmental sustainability. The former aims to reduce environmental risks, waste production, and waste disposal through recycling, reuse, and proper disposal (Suhaib & Fayaz, 2023). The intensification of agricultural practices and the associated production processes has led to a considerable amount of agro-industrial waste. This increase in production has put considerable pressure on the environment and has had a negative impact on the resources of the agricultural system. One of these agro-industrial wastes is phosphogypsum, the calcium sulphate hydrate that is a by-product of the production of fertilisers, especially phosphoric acid, from phosphate rock and can be used as a soil conditioner or agricultural fertiliser due to its physical and chemical properties (Elbagory et al., 2024; Mesić et al., 2016; Pliaka & Gaidajis, 2022).

Phosphogypsum has been used on agricultural land since the 1980s to replace limestone in the improvement of saline and alkaline soils. In particular, it has been used in highly weathered, nutrient-poor soils, in alkaline soils with dense subsoil horizons or those prone to dispersion and surface crusting, in acidic soils with high aluminium content, and in calcareous soils (Mesić et al., 2016). However, this type of use raises concerns about heavy metal contamination, effects on soil nutrients, leaching of pollutants into groundwater and natural radioactivity (Bituh et al., 2021). The radioactivity of phosphogypsum is mainly enriched in uranium (^{238}U) and thorium (^{232}Th). The main radiotoxic element in the environment associated with the production of phosphoric acid is uranium, which passes from the immobile fraction of the phosphate rock into the bioavailable fraction of phosphogypsum. In the production of phosphate mineral fertilisers, ^{238}U has high levels, and 80–90% of ^{226}Ra is extracted to produce phosphogypsum, replacing Ca in the chemical composition (Saadaoui et al., 2017). All this suggests that before phosphogypsum is used in agriculture, it should be analysed for trace elements to avoid transfer of harmful elements to food and consequently exceed their regulatory limits in food products (Bituh et al., 2021). One possible solution is therefore the cultivation of energy crops whose purpose does not fall within the scope of food production, and one of these crop is *Arundo donax* L (AD).

Arundo donax L. (AD), commonly called giant reed or giant reed, is a plant that naturally grows spontaneously in different environments and is widespread in temperate and hot areas all over the world. The plant's adaptability to different environmental, soil and cultivation conditions, combined with its high biomass production and low cultivation costs, give AD many advantages over other energy crops (Corno et al., 2014). Although originally from Asia, the species is now distributed worldwide and is cultivated in many regions and under different climatic conditions. *Arundo donax* L. has no viable seeds and can therefore be considered a sterile plant, however, the risk of invasion in flooded areas can be high (Nocentini et al., 2018). In general, AD has a large biomass potential requiring a lower input, and a wide range of climatic conditions and soil types (including polluted ones) are suitable for its production (Jámbor & Török, 2019).

In the Republic of Croatia, mineral fertilizer production is carried out in "Petrokemija d. d." – Kutina, where the generated technological waste is disposed of. The production process of phosphoric acid is carried out by the dihydrate process, by which, in addition to the main product phosphoric acid, a secondary product calcium sulfate in dihydrate form - phosphogypsum - is formed. The production facility consists of the following production units: phosphate grinding section, reaction and filtration section, evaporation section, weak and strong acid storage, neutralization section and phosphogypsum disposal section. The daily production capacity is 500 t of weak acid and 550 t of strong acid (expressed as 100% P_2O_5) and 36 t of hexafluorosilicic acid (expressed as 100% H_2SiF_6). For every ton of phosphoric acid produced, about five tons of phosphogypsum is produced by the dihydrate process, which is permanently disposed of at a specially arranged landfill (Leaković et al., 2012). During the production of phosphoric acid, waste water contaminated with fluorides and phosphorus is also produced. Such waste water is treated by neutralization with lime before discharge into the natural receiver hydrate. The resulting product of neutralization is calcium fluoride (CaF_2), which is treated as non-hazardous waste. They leave in specially built lagoons (Leaković et al., 2012).

Existing phosphogypsum landfill near Kutina can be remediated using either the “in situ” or the “ex situ” method. When selecting a technical reclamation solution, the most important criteria are the environmental impact, the location and the reclamation costs. The implementation of reclamation and revegetation measures would continuously reduce the potential negative impact of waste on the environment and natural resources, in particular by reducing pollution of surface and groundwater, soil and air, as well as reducing risks to human and animal health. The reclamation of the phosphogypsum landfill near Kutina was carried out by covering the landfill with an upper sealing layer using reclamation materials as a substrate for planting and existing phosphogypsum is stored in the existing storage cells. The reclamation of the upper layer is carried out with a substrate consisting of a mixture of sludge and phosphogypsum in a ratio of 80:20, supplemented with additional materials (sand or soil) to achieve better stability of the sealing layer. Such a substrate often has excellent properties that surpass the quality of conventional soil conditioners. Namely, one of the potential soil amendments, among others, is wastewater sewage sludge. It can be used to increase the biomass yield, the absorption potential of the plants, the amount of soil organic matter and to immobilize the metals in soil (Zgorelec et al., 2020). The use of sewage sludge offers a more cost-effective method of revegetating the landfill and at the same time reduces the need to apply humus soil as a cover layer. As the application of a humus layer represents an additional financial burden for landfill remediation, sewage sludge treated with phosphogypsum can be used as a cover substrate in combination with the application of calcium fluoride sludge. However, the use of sewage sludge for landfill remediation is permitted provided that the sewage sludge fulfils all prescribed standards and legal requirements. As the sewage sludge is expected to have a persistently favourable physical and chemical composition after the reclamation process with phosphogypsum, it is expected to serve as a suitable substrate for the cultivation of energy crops used as cover vegetation on the landfill.

The aim of this study was to investigate the growth of the energy crop AD on different substrates and its possible use as soil conditioner. The main objective was to determine and compare the influence of 2 different materials: (i) phosphogypsum (FG - $CaSO_4 \times 2H_2O$) and (ii) substrate (CaF_2 + municipal sewage sludge) on the total content of S, Ca, Pb, Zn, As and U in the soil, as well as biomass yield and yield components.

MATERIALS AND METHODS

Energy crop Arundo donax (AD)

The rhizomes of AD (~ 20 cm with 4-6 plant buds) were planted on 12/04/2023. The first harvest took place on 27/02/2024. The quality and quantity of growth of the energy crop elephant grass (AD) and the substrate were measured after harvest: yield (mass) per pot and yield components (number of shoots and plant height per pot).

Substrates - waste materials as potential soil amendments

(1) phosphogypsum (FG - $CaSO_4 \times 2H_2O$) – waste material took from Petrokemija mineral fertilizer plant (from landfill in Lonjsko Polje, generated during the production of phosphoric acid)

(2) substrate for reclamation of phospohogypsum landfill made from municipal sewage sludge from the Zagreb Wastewater Treatment Plan and CaF_2 [non-hazardous waste generated during the production of phosphoric acid] and was mixed in 80:20 ratio.

(3) Soil used as a control in experiment was taken from testing field Maksimir (pH_{KCl}=7.56; OM= 2.2 %; TN=0.188 %; TS=0.05 %; P-AL >400 $mgkg^{-1}$; K-AL = 139 $mgkg^{-1}$). Soil samples were taken before the establishment of the trial (2023) and after the first harvest (2024).

Experimental design

An experiment consisted of 5 different treatments (different ratios and combinations applied to the soil) in 3 replicates. The treatments were (Figure 1): I - soil (100 %); II - substrate (100 %); III - soil + substrate (50 % / 50 %); IV - FG + soil (50 % / 50%) and V- FG + substrate (50 % / 50%).

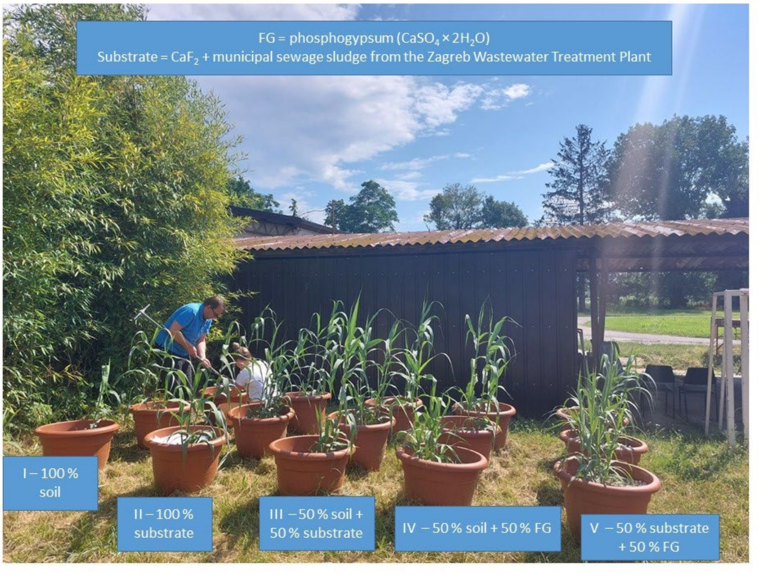

Figure 1. Experiment scheme

Study parameters and methods

In the table 1 all studied parameters and used methods are defined.

Table 1. Methods used, followed by a specific protocol for each parameter

Parameter	Unit	Method	Protocol
Drying/grinding/ seeding/homogenization	-	Preparation of soil samples	ISO 11464:2006(ISO 11464, 2006)
pH_{KCl}	-	Determination of the pH value in 0.01 M $CaCl_2$, 1 M KCl and H_2O in a ratio of 1:2.5 (m/v)	ISO 10390:2005(ISO 10390, 2005)
plant available phosphorus (P-AL) and potassium (K-AL)	mg kg^{-1}	in AL extract (AL method) in a ratio of 1:20 (m/v) (spectrophotometer, Hach DR/2000, 1996 and flame photometer, Jenway, PFP7, 1999)	Škorić 1982(Škorić, 1982)
determination of total elements (from Mg to U)	mg kg^{-1}	Soil quality — Screening soils for selected elements by energy-dispersive X-ray fluorescence spectrometry using a handheld or portable instrument (pXRF Vanta, Olympus, 2019)	ISO 13196:2013(ISO 13196, 2013)
TOC and TC	%	Dry combustion method, Vario Macro CHNS (TC)	ISO 10694:2004(ISO 10694, 2004)
Organic matter (OM)	%	Soil quality — Determination of organic carbon by sulfochromic oxidation	ISO 14235:2004(ISO 14235, 2004)
total N	%	Soil quality — Determination of total nitrogen content by dry combustion ("elemental analysis")	ISO 13878:2004(ISO 13878, 2004)
total S	%	Soil quality — Determination of total sulfur content by dry combustion	ISO 15178:2005(ISO 15178, 2005)
yield (mass fresh and dry)	g pot^{-1}	Gravimetric	ISO 712:2009(ISO, 2009)
yield components - number of shoots			
yield components - plant height	cm		

Statistical analysis and quality control

Statistical analysis was done with the use of statistical software SAS 9.1 (SAS Inst. Inc.), One-Way ANOVA and post-hoc (Fisher LSD) test were used for processing of data. The threshold of significance was 5% for all tests. Quality control was included. Measurement accuracy and methods precision for descriptor determinations were checked using reference materials (ISE 851 and 970 for soil, Wageningen University) and were satisfactory.

RESULTS AND DISCUSSION

Regarding the pH, treatment I, II and III had significantly higher pH (slightly alkaline) than those with FG (natural; IV and V) (Figure 2). Organic matter (OM) was significantly the highest in the treatment with municipal sewage sludge substrate (II, highly humic; 7%), while in pure soil OM were medium (I; 2.2%) and the lowest. The total S content were significantly the highest in treatment V with 2480 mgkg^{-1}, and total N content were significantly the highest in the treatment with municipal sewage sludge substrate (II, very rich supply; 0.396%).

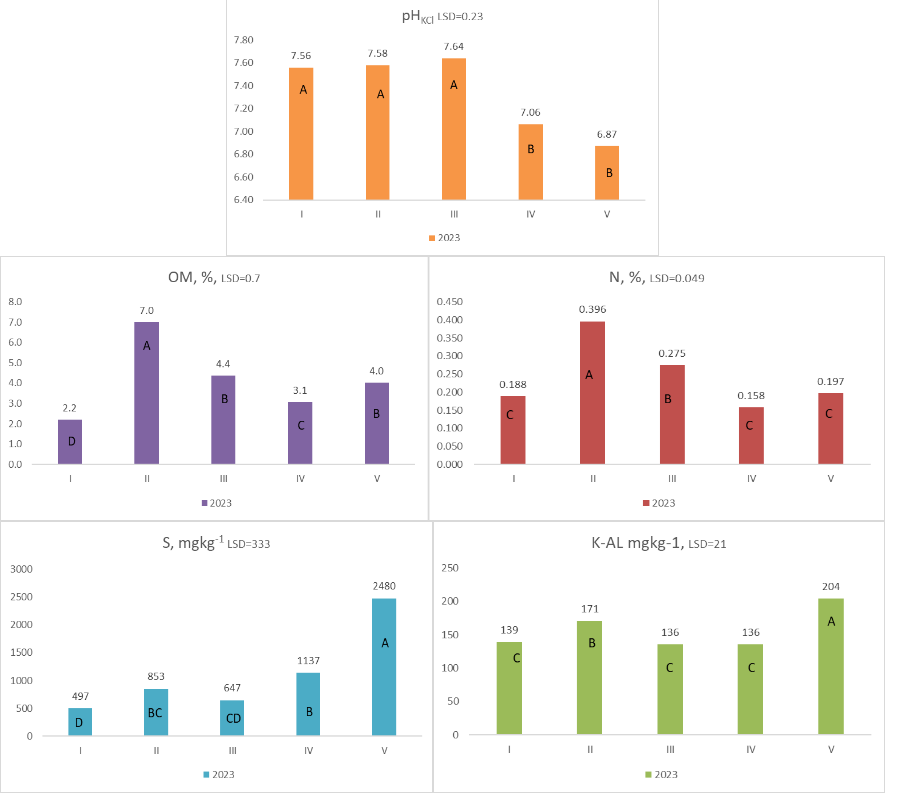

Figure 2. Results of soil/substrate analysis: pH, OM, total N, total S and plant available potassium (mean value marked with the same capital letter between treatments are not statistically significant, Fisher test, p<0.05)

The optimal CN and NS ratio (Kisic et al., 2019) were recorded just for treatment III (10 and 1, respectively). The CN ratio in the soil higher than 15 is an indicator that plants have a limited content of nitrogen in the soil, while the value of CN ratio lower than 10 is an indicator of a limited decomposition of organic matter in soil (Kisic et al., 2019). In all treatments CN ratio were in the range from 10-15.

Soil was very rich supply with plant available phosphorus (P-AL) in all treatments (> 400 $mgkg^{-1}$) and plant available potassium (K-AL) was significantly the highest in treatment V with 204 $mgkg^{-1}$ (good supply) in comparison to other treatments (Figure 2).

The significantly highest yield of AD was recorded in treatment II and III (with sludge). The significantly highest plants were observed in treatments from I to III (soil and sludge). The lowest number of shoots per pot was recorded in I (pure soil) (Figure 3).

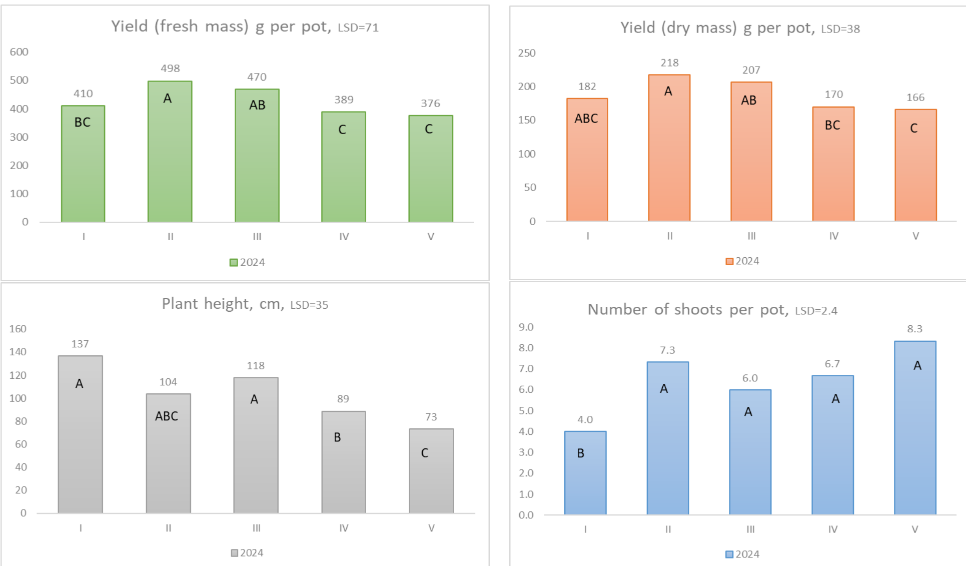

Figure 3. Results of yield and yield components (mean value marked with the same capital letter between treatments are not statistically significant, Fisher test, $p<0.05$)

Figures 4 shows total elemental content in soil/substrate. The As content ranged from 10 $mgkg^{-1}$ (II, 2023) to 19 $mgkg^{-1}$ (IV, 2023 & 2024) and the Pb content from 18 $mgkg^{-1}$ (IV, 2023) to 86 $mgkg^{-1}$ (II, 2024). The Ca content ranged from 16 807 $mgkg^{-1}$ (I, 2024) to 214 225 $mgkg^{-1}$ (V, 2024) and the U content from 5 $mgkg^{-1}$ (I-III, 2023 & 2024) to high 111 $mgkg^{-1}$ (V, 2023). The Zn content ranged from 99 $mgkg^{-1}$ (I, 2024) to 576 $mgkg^{-1}$ (II, 2024) and the Zn content in all treatments except in clean soil (I) was above the MAC (OG 71/19)(Official Gazette, OG 71, 2019) value prescribed by Croatian legislation for agricultural soils (200 $mgkg^{-1}$, for $pH_{KCl} > 6$).

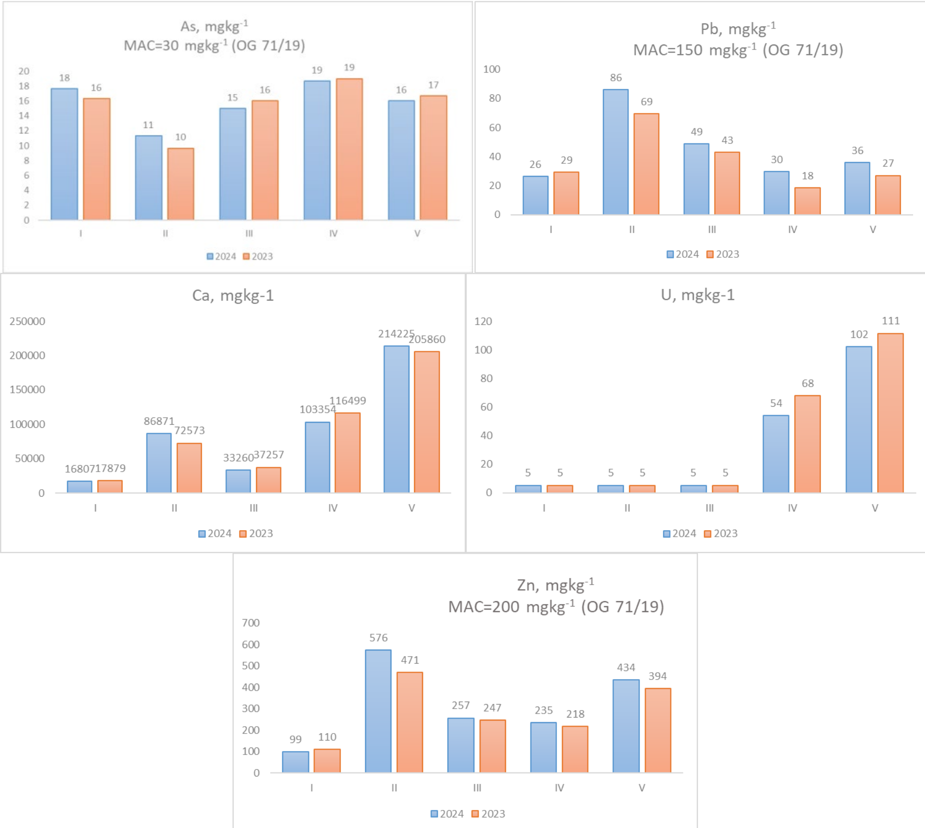

Figure 4. Results of soil/substrate total elemental analysis: As, Pb, Ca, U and Zn

CONCLUSIONS

Treatment with pure soil (I) in comparison to other treatments in first year of investigation shows the best results regarding the plant height. Treatments with sludge (II & III) have had the highest yield, OM and total N content, additionally pure municipal sludge treatment (II) shows high content of Pb and Zn in comparison to all other treatments. FG treatments (IV and V) shows high content of Zn, Ca, S, K-AL and very high U content in comparison to all other treatments. The Zn content in all treatments except in clean soil (I) was above the MAC (OG 71/19) value prescribed by Croatian legislation for agricultural soils. We should be aware of the high content of some parameters in waste materials, such as U and S in FG and Zn in sewage sludge, and prepare the quantities in the substrate mixtures appropriately and carefully.

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50. ACTUAL TASKS ON AGRICULTURAL ENGINEERING

Preliminary communication

ANALYSIS OF VEGETATION FIRES FROM AGRICULTURAL FARMINGS IN WEST BANAT

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ABSTRACT

The present paper try to evaluate the vegetation fires in agricultural farming in West Banat (Timis County), using the official records of fire events in last three years (2021, 2022 and 2023). The aim of the study was: to evaluate the period (day, moth, year) of fire, causes of the fire, the surface of affected area by fire, effects and consequences on the land, vegetation, objects and human beings, the first ignited material identified and locality area. Was analysed a number of 262 vegetation fires, official reported in 2023 year, 698 in 2022 year and 550 in 2021 year. Collected data were proceeded for statistical analysis using Microsoft Excel and STATGRAPHICS Centurion 19. The relevance was verified by Fisher test, and ANOVA, was used for possible relations between month, number of fires, causes of the fire identified, the size of the surface of affected area by fire, effects and consequences on the land, vegetation/culture, objects or human beings, the first ignited material identified and locality area. A hazard map can be elaborated based on vegetation fire with different possible selection. The paper results can provide a perspective on the relationship between land vegetation and potential fire hazard in agricultural production systems. Also, we concluded that different management practices associated to weather conditions and air water content, applied in the agricultural systems, can change the fire hazard in agricultural systems.

Keywords*: vegetation fire, assessment, causes, hazard map, relationships*

INTRODUCTION

Important and integral part of many ecosystems, fire is a natural phenomenon affecting biological processes and species, including decomposition or accumulation of biomass.

Regarding origin and outbreak, the fire in the agricultural landscape is mainly determined by the weather (usually through drought, by lack of water) and different accidentally situations, including self-ignition (even the law punish it) (Aponte et al., 2016; Fernandez-Anez et al., 2021; Winkler et al., 2023). Generally, as extreme weather has become more frequent in European area, due to climate change, the fire protection in agriculture became an important activity in conditions of significant economic impact of agricultural field fire and increasing of number and intensity of fire consequences (Li et al., 2022; Maxwald et al., 2022). In such conditions became important the aim to determine the extent of the number, wildfire area and direct consequences, as well as the degree of change in vegetation caused by the fire (Collins et al., 2018). One of the most important fire risks in agriculture is the complexity of agricultural equipment (Tucu et al., 2010; Babanatis Merce et al., 2018), combined with employees' low qualification and poor understanding of fire risks as work undesirable event, in condition of low effect of authority prevention policies (Crisan et al., 2017; Tucu, A., 2021; Tucu, A., 2023).

The paper aim to evaluate the vegetation fires in agricultural farming in West Banat (Timis County) based on the official records of fire events in last three years (2021, 2022 and 2023), by analysing simultaneously the period (day, moth, year) of fire, causes of the fire, the surface of affected area by fire, effects and consequences on the land, vegetation, objects and human beings and the first ignited material identified and locality area.

METHODS

Place of the analysis was the Timis county (figure 1, Google maps), area situated in west of Romania, central Europe, almost plain, less hill and a bit of the mountain area.

Figure 1. Place of study

Relatively to proposed area, were extracted from official statistics information regarding time of fire (year, month, day, hour and minute), cause (1-open fire in open space; 2- open fire in a closed space; 3- smoking in places not permitted or in unprotected places; 4 - children´s play with fire; 5- electrical damage; 6 - self-ignition; 7- sparks from locomotives, vehicles (agricultural machines); 8- mechanical sparks; 9 - intentional use of ignition source to start the fire; 10 - smoking while sleeping; 12 - other cases; 13 – thunderbolt; 14 - the action of some responsible persons (including self-ignition); 15 - solar heat (radiation) accumulated; 16 - inadequate thermal protection), category of the affected area surface, [m^2] (1- <10 m^2; 2- between 11-100 m^2; 3- between 101-1000 m^2; 4- between 1001-10E4 m^2; 5- >10E4 m^2), type of agricultural exploitation (1- dry vegetation; 2- vacant land; 3- yard, garden; 4 – stubble; 5- field of grain; 6 – pastures; 7- garden, park; 8- cemetery; 9- agricultural machines and equipment; 10- animal shelter; 11 - fodder warehouse; 12 - garbage dump; 13 –forest; 14 - orchard or vineyard; 15 - silos, barns; 16 –greenhouses), concrete effect of the fire, first material ignited (concrete indication) and locality (concrete indication).

After collecting, the information will be prepared using Microsoft Excel for statistical analysis. Firstly, new group of data according to the relevance will realised, using the significative factors and consequences. The statistical relevance will be verified by Multiple-Sample Comparison, ANOVA and Multiple Range Tests, if existing influences. Finally, using Multiple Regression possible relations for prediction will be determined.

RESULTS

Table 1 presents the most important causes (that determined each, more than 3% of total fires (1510 in the full period)) and their weight (in % from total fires on the same cause), correlate with burned surface. Similarly, in table 2 can be observed the weight of different burned surfaces correlate with type of agricultural exploitation, and in table 3 the correlation between month and weight of burned surface.

Table 1. Influence of causes on the weight of category of burned surface

Surface Cause	**<10**	**11-100**	**101-1000**	**1001- 0E4**	**>10E4**
1	8.15	22.67	26.25	17.65	25.27
3	12.38	20.95	38.10	16.67	11.90
5	18.00	36.00	26.00	8.00	12.00
12	28.95	21.05	13.16	7.89	28.95
2	27.27	22.73	36.36	4.55	9.09
CAv	18.95	24.68	27.97	10.95	17.44

CAv- average of cause`s weight on burned surface

The results of Multiple-Sample Comparison for ANOVA, F-ratio which is equal 3.5928E-8 (is a ratio of the between-group estimate to the within-group estimate) and the P-value of the F-test greater than 0.05, confirm there is not a statistically significant difference between the means of the 5 selected causes on the burned surfaces. The Multiple Range Tests also confirm there are no statistically significant differences between any pair of means of cause`s weight at the 95.0% confidence level. The Box-and-Whisker Plot confirm also the previous conclusion.

Table 2. Influence of type of agricultural exploitation on the weight of category of burned surface

Type	<10	11-100	101-1000	1001-10E4	>10E4
1	5.37	16.53	30.99	19.97	27.13
2	17.61	34.22	31.23	8.64	8.31
3	19.31	24.83	47.59	7.59	0.69
4	2.42	4.84	8.87	29.03	54.84
5	0.00	6.25	10.42	12.50	70.83
6	6.90	27.59	20.69	20.69	24.14
EAv	8.60	19.04	24.96	16.40	30.99

EAv- average of type of agricultural exploitation`s weight on burned surface

Table 3. Influence of month on the weight of category of burned surface

Month	<10	11-100	101-1000	1001-10E4	>10E4
1	45.71	40.00	14.29	0.00	0.00
2	17.14	24.29	38.57	10.00	10.00
3	6.40	18.00	28.80	17.20	29.60
4	14.77	31.82	26.14	19.32	7.95
5	29.17	43.75	20.83	4.17	2.08
6	7.41	30.37	32.59	14.81	14.81
7	4.67	20.33	26.92	21.70	26.37
8	5.88	17.99	25.61	19.38	31.14
9	15.73	24.72	33.71	6.74	19.10
10	14.00	25.00	21.00	13.00	27.00
11	15.00	40.00	35.00	0.00	10.00
12	18.18	45.45	22.73	9.09	4.55
MAv	16.17	30.14	27.18	11.28	15.22

MAv- average of month`s weight on burned surface

Regarding the analysis of effects of causes, the same analysis indicated a statistically significant difference between the means of the 5 variables at the 95.0% confidence level (table 4, ANOVA results for influence of causes on the burned surfaces).

Table 5 includes the results for Multiple Range Tests denoting a statistically significant difference for pairs 1001-10E4 versus 101-1000, and 1001-10E4 versus 11-100. The same conclusion came from the examination of Box-and-Whisker Plot in this situation (figure 2), statistical significance being maximum between 1001-10E4 versus 101-1000, and 1001-10E4 versus 11-100.

Table 4. ANOVA results for influence of causes on the burned surfaces

Source	Sum of Squares	Df	Mean Square	F-Ratio	P-Value
Between groups	874.99	4	218.75	3.23	0.0336
Within groups	1352.62	20	67.63		
Total (Corr.)	2227.62	24			

Regarding influences between agricultural exploitation and burned surfaces, a similar situation occurred: since the F-ratio is equals 1.7778 and the P-value of the F-test is greater than 0.05, there is not a statistically significant difference between the means of the 5 variables at the 95.0% confidence level, so the agricultural exploitation did not influence statistically significant the burned surfaces (relevant figure 3).

Table 5. The results for Multiple Range Tests surfaces/causes

Contrast	Sig.	Difference	+/- Limits
<10 - >10E4		1.51	10.85
<10 - 1001-10E4		7.99	10.85
<10 - 101-1000		-9.02	10.85
<10 - 11-100		-5.73	10.85
>10E4 - 1001-10E4		6.49	10.85
>10E4 - 101-1000		-10.53	10.85
>10E4 - 11-100		-7.24	10.85
1001-10E4 - 101-1000	*	-17.02	10.85
1001-10E4 - 11-100	*	-13.73	10.85
101-1000 - 11-100		3.29	10.85

* Denotes a statistically significant difference.

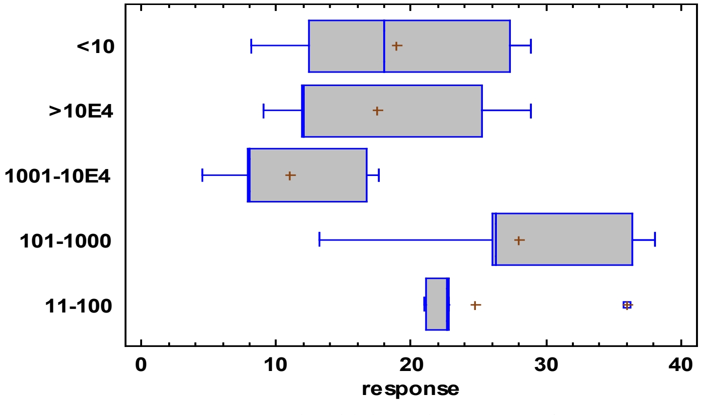

Figure 2. Box-and-Whisker Plot surfaces/causes

The maximum statistically significant difference was obtained for the relationship between month and category of burned surface, that determined using of multiple regression for establishing a prediction mathematic model for simulate the weight of fires in Timis area. Table 6 presents the summary output and table 7 ANOVA and regression results. Residual output and probability output results are presented in table 8. The prediction model has a good value of the coefficient of multiple correlation R square = 0.739.

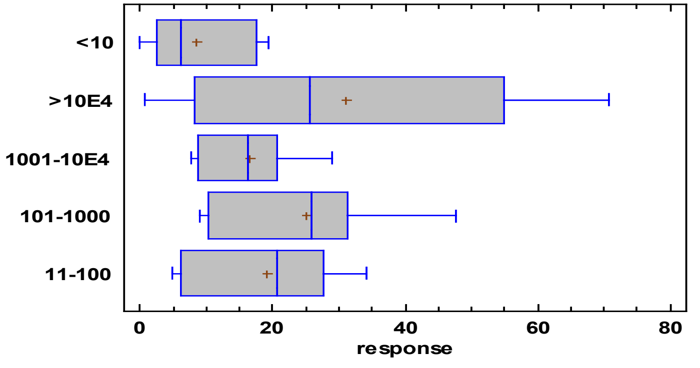

Figure 3. Box-and-Whisker Plot for type of exploitation/burned surfaces

Table 6. The summary output of multiple regression type of exploitation/burned surfaces

Regression Statistics	
Multiple R	0.859
R Square	0.738
Adjusted R Square	0.446
Standard Error	2.311
Observations	12

Table 7. ANOVA and regression results for multiple regression exploitation/burned surfaces

	df	SS	MS	F	Significance F
Regression	5	105.6060797	21.12121594	4.942264356	0.038612787
Residual	7	37.39392031	5.341988615		
Total	12	143			
	Coefficients	**Standard Error**	**t Stat**	**Lower 95%**	**Upper 95%**
Intercept	-27.00272845	12.90583988	-2.092287577	-57.5202	3.514734
<10	-0.029977166	0.136109251	-0.22024341	-0.35182	0.29187
11-100	0.681146513	0.177859213	3.829694851	0.260576	1.101717
101-1000	0.18032418	0.159029907	1.13390106	-0.19572	0.55637
1001-10E4	0	0	65535	0	0
>10E4	0.562095233	0.205496379	2.735304804	0.076174	1.048017

The prediction model for vegetation fire will express the weight of possible fire, Wf:

$$Wf = -27.00272845 - 0.029977166 * \big(W(<10)\big) + 0.681146513 * (W(11-100)) + 0.18032418 * \big(W(101-1000)\big) + 0.562095233 * \big(W(>10E4)\big) \quad (1)$$

Table 8 Residual output and probability output results

Observation	Predicted	Residuals	Standard Residuals	Percentile
1	1.4488	-0.4488	-0.2542	4.1667
2	1.6018	0.3982	0.2255	12.5
3	6.8974	-3.8974	-2.2078	20.8333
4	3.4115	0.5885	0.3334	29.1667
5	6.8508	-1.8509	-1.0485	37.5
6	7.6664	-1.6666	-0.9440	45.8333
7	6.3841	0.6159	0.3489	54.1667
8	7.1988	0.8011	0.4538	62.5
9	6.1780	2.8219	1.5986	70.8333
10	8.5696	1.4304	0.8103	79.1667
11	11.7257	-0.7258	-0.4111	87.5
12	10.0666	1.9333	1.0952	95.8333

CONCLUSIONS

There are a lot a possible factor influencing the fire in the agricultural landscape, mainly determined by the lack of water or different accidentally situations, including self-ignition (perceived sometimes as part of agricultural technology). Starting at local conditions and official statistic in Timis County present paper studied the possible correlations between causes, month of the year (seasons), type of agricultural exploitations and consequences of the vegetation fires expressed in 5 classes of burned surfaces. Due the absence or less statistical significance of some factors, could be concluded that different management practices associated to weather conditions and air water content, applied in the agricultural systems, can change the fire hazard regarding vegetation fire in agricultural systems (control, monitoring, equipment improvement etc.).

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50. ACTUAL TASKS ON AGRICULTURAL ENGINEERING

Review paper

KEY CONCEPTS REGARDING UAV TECHNOLOGY USED IN CROP MONITORING

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ABSTRACT

UAV Technology offers a wide range of advantages for crop monitoring in agriculture. From monitoring plant health and managing water resources to detecting pests and applying treatments, drones represent a powerful tool for modern agriculture. The use of drones in this field can lead to improved efficiency, reduced costs, and increased quality production. Our study highlights several extremely important elements of unmanned aerial vehicle (UAV) technology used in agriculture. To this end, an experimental study is being conducted in the orchard plantation on the campus of the Politehnica University of Bucharest using a DJI Mini 4 Pro commercial drone. The results obtained are visualized and reported in a user-friendly manner. Interactive detailed maps showing crop status, plant health, etc., are particularly useful tools for determining the optimal time for harvesting based on crop condition and maturity, as well as for improving irrigation systems and conserving water.

Keywords: *GPS, plantation, drone, OcuSync, DJI Mini 4 Pro*

INTRODUCTION

DJI commercial drones are among the most popular and widely used in various industries, not only due to their advanced technology but also because of their ease of use and reliability. Beyond any marketing objectives, it should be noted that statistically, Da-Jiang Innovations dominates the global market for commercial and consumer drones, holding a significant market share of over 75% (Bender, 2021). Rightly so, they are among the most popular and utilized in various industries, primarily due to their highly advanced technology, as well as their ease of use and reliability.

The highly diverse models released by DJI, such as the Phantom 4 RTK used in topography and mapping, the Mavic 3 Enterprise with advanced mapping and inspection functions, the Matrice 300 RTK widely used in industrial inspections, search and rescue missions, and precision agriculture, or the Agras T30 specifically designed for crop spraying in precision agriculture, are well-known for their robust design and technology that ensures reliability in various flight conditions. Additionally, the superior quality of images and videos captured with high-resolution cameras or advanced automation and AI features allows for the execution of complex missions with minimal human intervention.

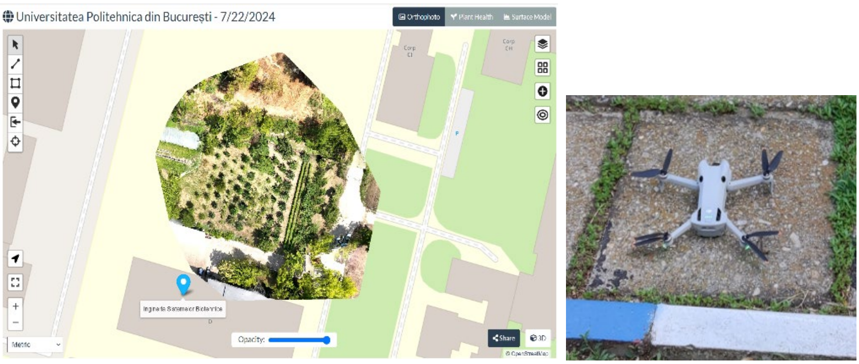

Figure 1. The monitored area (left) and DJI Mini 4 Pro drone (right)

The theoretical fundamentals of implementing drone technology in monitoring and surveillance of crops in precision agriculture have already been investigated in numerous research papers. A simple search on Google Scholar generated approximately 7,850 articles in 0.51 seconds, including those by Hafeez et al. (2023), Zhang et al. (2021), Campos et al. (2019), Singh et al. (2022), and Kasimati et al. (2023). These studies discuss the potential of UAV technology for applying monitoring and mapping techniques in agriculture by collecting large amounts of data to track the development and dynamics of crop growth and structure over time. They also address the importance of mission planning, limited flight time, and weather conditions that influence drone performance and stability.

Popescu et al. (2023) highlight new research trends in orchard monitoring, emphasizing the implementation of neural networks (as a core element of artificial intelligence in image processing) in unmanned aerial vehicle (UAV) technology. They employed a standard review method by selecting and analyzing publicly available works on the internet from the period 2017-2022, using keyword combinations related to the topic as search elements.

Bender (2021) proposes a methodology based on software and hardware radio elements for detecting DJI drone identification packets (IDs) transmitted via Wi-Fi and OcuSync technologies, as well as a functional prototype equipped with two open-source software-defined radio (SDR) devices as a DJI OcuSync detection system. Real-time monitoring of drones requires detection capabilities with reliable radio frequency throughput. Protzman (2022) analyzes radio frequency signals containing GPS information, which should not be made public, regarding the location of DJI drones and the time of recording. Demodulation of recordings made with an Ettus B205-mini device at a sampling rate of 30.72 MSPS, at a frequency of 2.4 GHz, was performed using Octave 5.2.0 and MATLAB programs.

One of the objectives of our research, which took place at the fruit orchard location on the Politehnica University of Bucharest campus (see Fig. 1), was to gain a more comprehensive understanding and provide a clearer explanation of key concepts such as aircraft identification and flight data, the quality of the communication link between the drone and the remote control, and the geographical context of the flight. A more detailed knowledge of these aspects will enable drone users in the agricultural industry to operate and successfully complete complex missions in a wide range of environments.

CONCEPTS REGARDING DRONE TECHNOLOGY

The determination of the aircraft's position is achieved using the GPS receiver on the drone, which calculates its exact position based on the time it takes for signals to reach from multiple satellites (usually at least four – see Fig. 2a). This technique is known as triangulation or multilateration. The GPS data is transmitted to the drone's control unit, which uses this information to determine the drone's exact position and to adjust the flight trajectory if necessary.

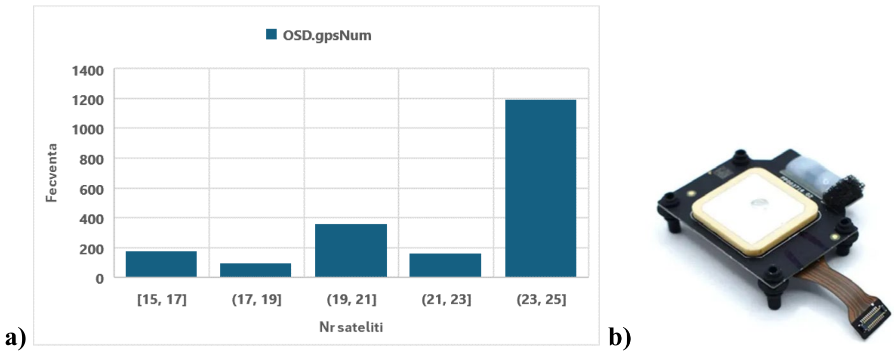

Figure 2. Communication between a drone and GPS satellites: the number of satellites connected to the drone during the mission (a) and GPS receptor Ublox M8P (b)

Communication between a drone and GPS satellites is essential for precise navigation and automated operations. This communication involves several processes and technologies.

The drone's GPS coordinates, altitude, pitch, roll, or yaw angles, and the return path to the takeoff point are sequentially converted. Each GPS coordinate (longitude and latitude) is encoded into two bytes (16 bits) using the following calculation method (Bender, 2021):

$$scaledGPS = \frac{GPS\ Coordinate + 180}{360} \times 65535 \quad (1)$$

The drone is equipped with a GPS receiver (Fig. 2b) produced by Ublox, model M8N/M8P, which receives signals from GPS satellites. These satellites transmit radio signals containing information about their exact time and location. During flight, the drone communicates GPS data and other navigation information in real time to the ground control center or other devices via communication channels such as radio, Wi-Fi, or cellular networks.

Modern GPS systems include safety and security measures to prevent interference and hacking. These measures include signal encryption and authentication checks, which allow drones to navigate precisely and perform various autonomous missions.

Drones primarily use GPS devices for navigation, but there are also other systems and technologies that can be used as alternatives or supplements.

Inertial Navigation Systems (INS) use accelerometers and gyroscopes to estimate the drone's position, speed, and orientation. The tilt, roll, and yaw angles can be converted into numerical values using a set of conditional instructions (Fig. 3 - 4). This system operates independently of satellite signals, making it ideal for areas without GPS coverage.

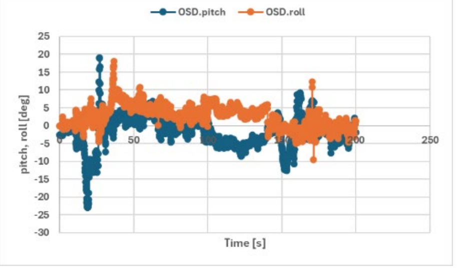

Figure 3. Angle pitch and roll On-Screen Display - OSD

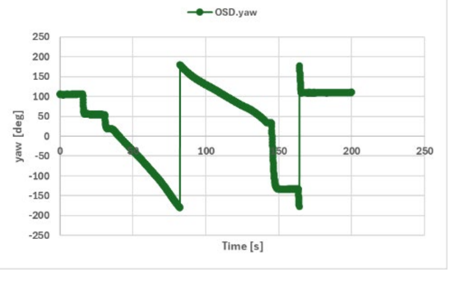

Figure 4. Angle yaw On-Screen Display - OSD

Visual odometry uses cameras and image sensors to track the drone's movement relative to its surroundings. Techniques in image processing are employed to calculate the drone's trajectory.

Magnetic sensor-based navigation (magnetometers) detects the Earth's magnetic field to determine orientation and is used in conjunction with other systems for more accurate navigation.

DJI Mini 4 Pro - signal encryption and authentication verification

DJI drone identification packages. The introduction of a secure drone identifier by DJI was motivated by several considerations. The use of an unconnected location identifier associated with a specific drone enables the integration of flight safety and security in public spaces, while also ensuring operator accountability, simultaneously fulfilling several essential objectives. To achieve this goal, DJI uses two encrypted communication protocols for data transmission, via the enhanced Wi-Fi system and OcuSync.

The DJI Mini 4 Pro, as part of the DJI drone lineup, comes with advanced security features to ensure signal encryption and authentication. Here's how these technologies are implemented:

A. Signal Encryption. DJI uses encryption to protect communication between the drone and its controller. This prevents interception and manipulation of transmitted data. The most common techniques include AES (Advanced Encryption Standard) encryption and Wi-Fi. If the drone uses Wi-Fi connections for video transmission or control, these are protected with standard network encryption.

B. Authentication Verification. To prevent unauthorized control or spoofing attacks, DJI implements several authentication verification measures such as secure pairing, firmware authentication, and controller authentication.

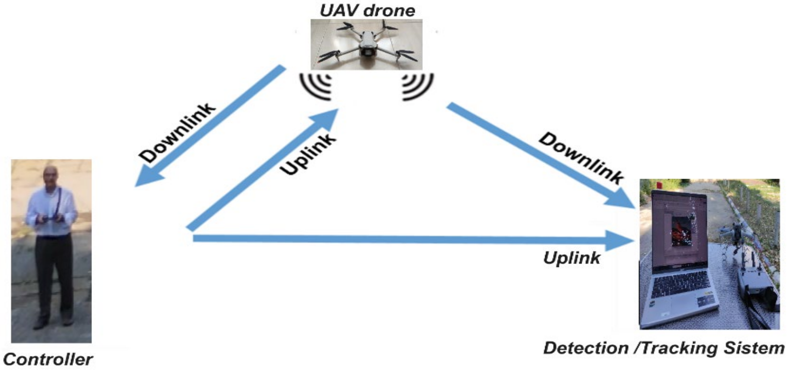

Figure 5. Detection and tracking diagram: video signal and telemetry (downlink) / drone control (uplink).

C. OcuSync Transmission. OcuSync is a wireless transmission system that is part of the Lightbridge family and provides HD video with low latency and control signal over a distance of up to 7 km at a resolution of 720P. It was first introduced with the DJI Mavic Pro model.

The DJI Mini 4 Pro uses this technology for video transmission and control because it offers several security advantages:

- Through adaptive frequency hopping, the system constantly changes transmission frequencies to avoid interference and reduce the risk of interception.
- For data encryption, OcuSync employs advanced encryption to protect the data transmitted between the drone and the controller.

With the OcuSync system, the ID identifier is transmitted by the drone using the same hardware as its general communication. For this purpose, it uses FHSS modulation on the 2.4 GHz and 5.8 GHz frequency bands. Specifically, even if a user forces communication within the OcuSync system to operate on 2.4 GHz or 5.8 GHz through the DJI Fly smartphone app, the drone's identification signals are still broadcast outside the band via the communication link (Aouladhadj et al., 2021).

The OcuSync system uses security protocols to encrypt transmitted data, ensuring that only authorized users can access and control the drone. Additionally, its advanced transmission technology is designed to withstand interference, thus maintaining a stable and secure connection even in environments with a high potential for electromagnetic interference. This helps protect data and maintain control of the drone under various operating conditions.

The example scenario from Fig. 5 for a drone equipped with a camera and telemetry sensors used for surveillance is:

- *Downlink*: The drone transmits live video footage and telemetry data (e.g., altitude, GPS coordinates) back to a ground control station.
- *Uplink*: The ground control station sends commands to the drone, such as adjusting the camera angle, changing the flight path, or initiating a specific operation based on the detected video feed.

In summary, a detection and tracking scenario involving downlink and uplink communications requires seamless integration of video streaming, telemetry data transmission, and control commands, all while addressing challenges related to latency, bandwidth, reliability, and security.

Video transmission locks onto a clear channel at startup and remains there unless interference is detected. The FHSS control link constantly hops around and above the OFDM video (Fig. 6). Latency is 160 - 170ms and one of the new big benefits of Ocusync was the ability to have multiple controllers and receivers with up to 4 devices in total.

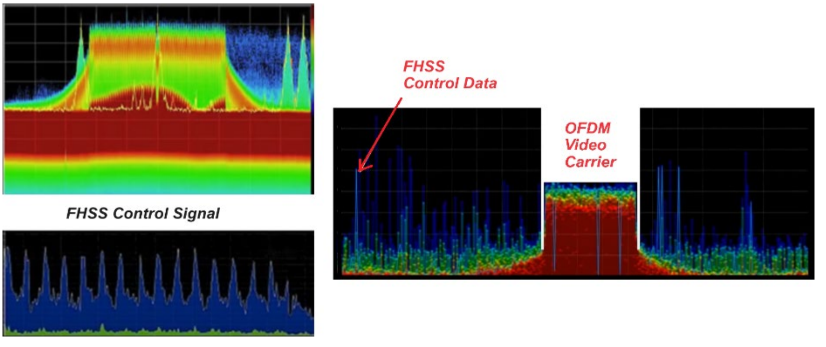

Figure 6. DJI Ocusync uses encrypted OFDM for video transmission with a form of FHSS signal for control links on the same frequency band (adapted from Write, 2014)

As additional safety measures for flight security, two methods are used:

- *No-Fly Zones* (NFZ) - Implementing no-fly zones in the drone's firmware, preventing flight in sensitive or restricted locations. The images shown in Fig. 7 provide a visual comparison of no-fly zones versus restricted authorization zones.
- *Geofencing* - the drone is programmed to avoid certain areas or to inform the user about flight restrictions. The technology can prevent flight in restricted areas, such as near airports or sensitive sites.

Mandatory identification elements of the aircraft are issued by an internal transmission module of the drone. The aviation authority of the European Union Aviation Safety Agency stipulates that a drone cannot take off if the elements listed in Table 1 are not included in its transmission messages.

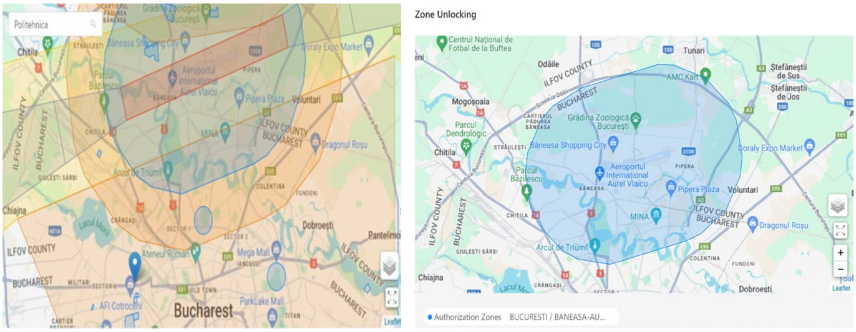

Figure 7. Comparison between no-fly zones (left) versus restricted authorization zones (right)

Table 1. Remote identification requirements for drones (adapted from Bender, 2021)

Elements	Performance	Example
Drone serial number and/or session identifier	Message transmission rate per second	DJI Mini 4 Pro Puju/ 1581F6Z9C
Latitude and longitude of the controller	44.43974267; 26.04523894	44.43974267; 26.04523894
Controller geometric altitude	78.432 [ft]	78.432 [ft]
Latitude and longitude of the drone	44.43974245; 26.04523872	44.43974245; 26.04523872
Drone geometric altitude	78.432 [ft]	78.432 [ft]
Drone speed	Message transmission speed per second	2.000779 [mph]
Timestamp	Synchronized with all other elements	7/17/2024; 03:46.5
Drone emergency status	On/Off	OFF

Viewing and analyzing the flight data of the DJI Mini 4 Pro civil drone can be done using applications and software provided by the manufacturer, DJI. Through official applications such as DJI Fly and DJI Assistant 2, as well as third-party platforms like Airdata UAV, DJI Flight Log Viewer, and DroneDeploy, users can monitor the drone's performance, analyze flight paths, and optimize drone usage for various applications. The flight data from this study can be freely accessed at the following web address: *https://www.phantomhelp.com/logviewer/N8TM4WYYIJNCX19J4GAQ6F3DQDX4FUX7*.

RESULTS AND DISCUSSION

The altitude variation graph of the drone over time is shown in Figures 8 and 9. From Figure 8, it can be observed that after takeoff, the drone ascends to an altitude of 24 meters, which was set as the flight path altitude. After completing the mission, to return to the takeoff point located between some trees, the drone climbs to an altitude of 34 meters for a safe landing. It then descends rapidly to an altitude of 3 meters; from this altitude, the landing on the ground occurs at a reduced speed.

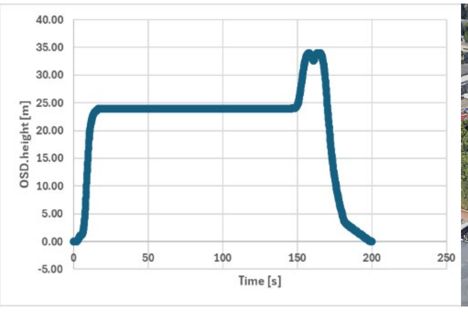

Figure 8. Drone altitude variation over time

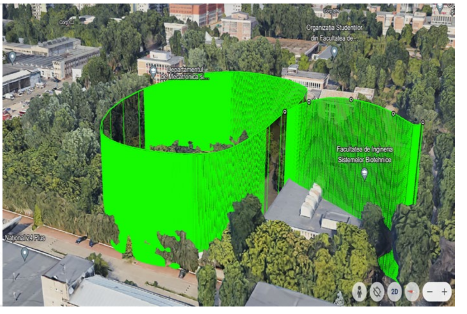

Figure 9. 3D visualization of the flight mission (Google Earth)

3D visualization of the DJI Mini 4 Pro drone's flight mission on Google Earth (see Fig. 9) is a process that involves exporting the flight data, converting it to KML format, and importing it into Google Earth. This process allows for detailed and contextualized analysis of the flight, providing valuable insights for optimizing operations and visually presenting the data.

The VARI (Visible Atmospherically Resistant Index) map obtained using the WebDOM online platform is a tool used for monitoring vegetation and plant health, based on images captured in the visible spectrum. This index is specifically designed to be less affected by atmospheric variations, making it useful in various weather conditions. The VARI index is calculated using the following formula:

$$VARI = \frac{\text{Green}-\text{Red}}{\text{Green}+\text{Red}-\text{Blue}} \tag{2}$$

where: Green - reflectance in the green band of the visible spectrum; Red - reflectance in the red band of the visible spectrum; Blue - reflectance in the blue band of the visible spectrum.

In the map presented in Fig. 10, areas with high VARI index values indicate healthy vegetation with active photosynthesis. Low VARI index values may signal plant stress caused by factors such as drought, diseases, or nutritional deficiencies, which may require additional irrigation.

The RDVI (Renormalized Difference Vegetation Index) is used to assess vegetation health based on remote sensing data, particularly multispectral images captured by drones. The RDVI index (Fig. 9, left) is a derivative of the NDVI (Normalized Difference Vegetation Index) and is used to enhance the interpretation of vegetation density and health.

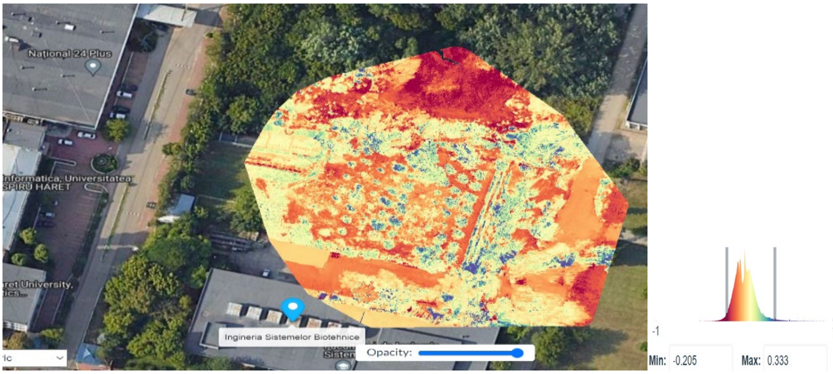

Figure 10. VARI (Visible Atmospherically Resistant Index) map

The RDVI index is calculated using the following formula:

$$RDVI = \frac{\text{NIR+Red}}{\text{NIR−Red}} \tag{3}$$

where: NIR (Near-Infrared) - reflectance in the near-infrared spectrum; Red - reflectance in the red spectrum.

Mapping is done by applying a color gradient to represent variations in RDVI, where darker colors indicate healthier and denser vegetation, while lighter colors signify stressed or sparse vegetation due to water shortages, diseases, or nutritional deficiencies (Jemaa et all, 2023).

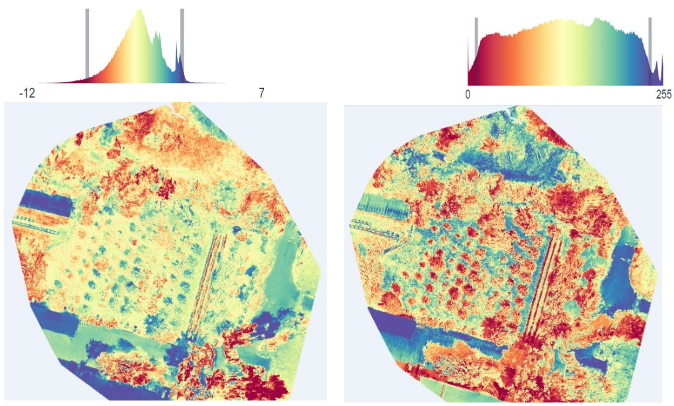

Figure 11. Map of the RDVI index (left) and color temperature (right)

The color temperature map in Celsius (Fig. 9, right), created using the online WebDOM platform through an easy-to-use web interface, represents an advanced tool for monitoring and analysis in modern agriculture, providing accurate and real-time data about environmental conditions. It helps farmers optimize resource use, reduce risks, and improve operational efficiency. Automated alerts and notifications assist in preventing damage caused by extreme weather conditions or sudden temperature changes. The use of such advanced technologies contributes to transforming agriculture into a more sustainable and productive field.

Although, as clearly indicated by Modica et al. (2020) and later by Roma et al. (2023), there are quantitative differences in the results obtained, it can be noted that our study demonstrates the robustness of the proposed framework in accurately assessing the health of trees in orchards or vineyards from UAV images.

CONCLUSIONS

Analyzing data collected by drones transforms raw information into valuable insights, providing support for informed and efficient decision-making across various fields. This contributes to optimizing processes, reducing costs, and improving outcomes in agriculture, industrial inspections, disaster management, and environmental monitoring. The use of drones and associated data analysis is a powerful example of applying advanced technology to address modern challenges.

The DJI Mini 4 Pro integrates advanced encryption and authentication technologies to ensure the security of communication between the drone and the controller.

Visualizing flight data in Google Earth provides real geographic context, helping to understand the interaction of the flight with the landscape, and offering a detailed perspective on altitude and flight direction.

Maps of the VARI, RDVI, or color temperature indices represent advanced tools for monitoring and managing crop health, providing precise and reliable data even under varying atmospheric conditions.

ACKNOWLEDGEMENTS

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50. ACTUAL TASKS ON AGRICULTURAL ENGINEERING

Preliminary communication

CROBOT - AUTONOMOUS ROBOTIC FLEET SYSTEM FOR WEED CONTROL

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ABSTRACT

The autonomous robot system cRobot is designed for the detection and environmentally friendly treatment of weeds on agricultural land. The robot consists of a versatile base platform that can accommodate various other tools that are important for the system. This allows cRobot to perform multiple functions, such as weeding, spraying, attaching various grippers (pickers) and using a range of other tools used in agricultural production.

By using artificial intelligence, it's able to automatically detect weeds in the crops with a high accuracy of 87% and then selectively remove them. The main innovation of this system is the use of laser technology for weed removal, which significantly reduces the need for herbicides and thus contributes to more sustainable agriculture and environmental protection.

The use of the cRobot improves the quality of the harvest and increases the number of plants per production unit, while at the same time optimizing costs and quickly recouping the investment. It also reduces the need for manual labor, allowing farmers to focus on strategic planning and improving production processes.

The system is designed as a fleet, i.e. it supports several robots in the field, which are charged at a solar-powered base station. The station also collects useful data that can be analysed, sent to the user and used for self-learning based on new information.

These highly autonomous robots can work 24 hours a day and, thanks to their precision, successfully treat weeds in crops such as corn, further optimizing agricultural treatments and improving crop quality.

Keywords: *cRobot, autonomous system, artificial intelligence, weeds, sustainable agriculture*

INTRODUCTION

Since sustainable, professional agriculture is inconceivable without advanced machinery, more and more efforts are being made to develop technology in agriculture. Although the digital transformation in agriculture began with equipping various systems with sensors and processors to collect data and automate basic functions, agricultural machinery manufacturers have also contributed to the progress of agricultural robotics by designing, developing and presenting attractive concept prototypes. Interest in agricultural robots has increased significantly over the last decade, although their penetration is not uniform around the world. The global market for agricultural robots is expected to reach USD 8.82 billion by 2025, with a compound annual growth rate (CAGR) of 24.7%. Compared to the robotics market (CAGR 10.5%), the breakthrough of robots in agriculture will be stronger (Mege et al., 2019). This is because the desired goal of greener agriculture from field to fork can only be achieved competitively if farmers can use the advanced tools that knowledge-based equipment can offer. It is therefore likely that the successful introduction of robotic solutions will occur before full autonomy becomes a practical reality.

Farm machinery manufacturers have made and continue to make significant efforts to evolve advanced vehicles into smart machines through the introduction of intelligent behaviour, automation and data collection devices. However, the complexity and size of such machines has so far prevented their commercial introduction for reasons such as reliability, safety and regulatory constraints. Manufacturers themselves are reluctant to launch advanced products that could be involved in accidents, jeopardizing their long-standing reputation.

This situation has led to the need to develop smaller robot platforms. This has not only reduced the risks associated with automation in the open field, but has also reduced the environmental footprint by replacing conventional diesel engines with electric drive systems.

cRobot was developed in cooperation with Purić d.o.o. - Damko Development Center from Samobor and the University of Zagreb, Faculty of Agriculture, Department of Agricultural Engineering. The aim of this concept was to demonstrate the advantages of a fleet system in which several robotic units are used on one production area. Such robots are indeed smaller and have a lower total mass. As a result, they do not cause any additional strain on the soil and fulfil all the necessary functions. The system is designed as an autonomous robotic system, uses computer vision, artificial intelligence (in an intelligent way that we control) and should enable a 24-hour presence in the field. Furthermore, this system is not intended to be very fast, but precise. Some of the goals of using cRobot for organic weed control on crops are to reduce the use of herbicides, improve crop quality and increase the number of stems per hectare, as well as to optimize costs and achieve a quick return on investment.

CROP HEALTH MANAGEMENT

According to Burks and Schmouldt (2008), the introduction of robotics in agriculture can create more jobs in the economy as a whole than it initially destroys. It is not realistic to simply replace workers with machines, as there are many crops for which there is a shortage of skilled labour. Crop health management involves detecting problems and taking action. Detection could be further improved through prediction, but the highly complex dynamics of weeds, diseases and pests have not yet led to universal commercial solutions. Weeds and pests pose different challenges and require different solutions. Thanks to the combination of artificial intelligence and computer vision, it has recently been possible to develop an intelligent application that makes it possible to spray only where weeds are present.

Crop protection is an important step in food production and can become a serious problem if not implemented correctly. Schneider et al. (2020) note that the situation in Europe varies greatly depending on the region. For example, countries in northern Europe with milder summers, more rainfall and extensive production are more affected by losses due to weeds. Southern countries, where climate change increases the frequency of heat waves and intensive production of specialty crops, are most affected by pest invasions or pest-borne diseases. Therefore, if a common policy to reduce the regulated use of plant protection products is proposed, a careful analysis of all users should be carried out. It is also expected that weed control will be carried out using physical technologies such as selective destruction of unwanted plants. Such environmentally friendly devices can be used under various conditions. The data obtained from such extensive tests will form the basis for artificial intelligence-based algorithms used in smart devices in the field.

ROBOTIC SOLUTIONS FOR WEED CONTROL

Changes in EU legislation and various initiatives to ban the use of certain pesticides, such as the glyphosate moratorium introduced by many European countries, have encouraged the return of mechanical weed control, which in turn has encouraged the development of small, electrically powered weed control robots. The smaller size of these robotic platforms has alleviated some of the complaints about reliability and safety. In addition, the highly specialized nature of these solutions reduces the complexity of the system, as only one task (weed control) is performed at a time.

CROBOT – 24-HOUR PRESENCE IN THE FIELD

cRobot consists of several basic elements: a polyvalent self-moving and controllable platform, a work unit (depending on the purpose) and a computer system (with a high degree of autonomy). The technologies considered in the development of cRobot are:

- Application of computer vision
- Artificial intelligence
- Laser technology (positioning and weed control)
- GPS and other positioning systems/methods
- Advanced battery systems
- Communication protocols (BT, LoRa, etc.).

The function of the robot is to use non-invasive methods to eradicate weeds, as one of the advantages is that it can easily move between the rows of plants. It is programmed to recognize the plants of the primary crops and the spectra of their green color, and the lasers then destroy the weeds that the robot isolates. The polyvalent robot platform can combine several different tools that are required in the system. For example, the cRobot can destroy weeds, spray, install various grippers (pickers) and a range of other tools used in agricultural production. The reason for introducing this new paradigm is to maintain soil quality.

The cRobot is powered by batteries, but also by a solar panel on the top of the robot. In this case, it can be restarted via the solar panel when it stops in the field, as one of its main objectives is to be constantly present in the field without the need for human intervention. It can be used on terrain with a maximum slope of 10% and is not suitable for more demanding, excessively wet terrain. It is designed for day and night use and can be used at all stages of crop growth. One of the remaining goals is to gain the ability to accurately map larger areas.

Figure 1. cRobot

cRobot uses artificial intelligence (AI) for the identification and ecological treatment of weeds in agricultural areas. The benefits of AI for crop production can be broadly focused on increasing the intelligence of agricultural equipment and increasing the efficiency and sustainability of agricultural operations. The automation of vehicles can be improved by AI algorithms that increase productivity and safety. Accordingly, agricultural operations can be improved through the use of AI-based expert systems that provide decision support and pave the way for data-driven agriculture as big data from the field becomes available.

DRIVE SYSTEM

During the development of the cRobot, particular attention was paid to the performance that the selected transport system must fulfil, including:

- Stability and flexibility (manoeuvrability)
- Minimal soil damage (through the irrigation process)
- Simple control.

Caterpillars and wheels are the most widely used running gear for the locomotion of agricultural vehicles. The main difference between the two systems is the contact area with the ground and consequently the pressure distribution (Grazioso et al. 2022). For cRobot, the caterpillar was chosen as the optimal drive. Caterpillars reduce the pressure on the ground, increase the overall pressure and friction and allow the weight of the vehicle to be distributed over a more even surface than wheels. For this very reason, tracked vehicles are more manoeuvrable on unpaved terrain than wheeled vehicles. The following parameters were defined for the optimum selection of a tracked drive:

- Mass of the cRobot with all associated equipment max. 70 kg
- Required speed approx. 0.05 m/s
- Height of the cRobot ≤ 1/2 width
- Length of the module max. 1 m
- Required mobility - turning radius ≥ 2 m.

The autonomy achieved in terms of battery and energy consumption is sufficient to cover the parameters set, and they can be further adjusted depending on the purpose. The autonomy targets are achieved and the rough preliminary data show that only 35% of the energy is consumed for traction, while 25% is needed for computing power and the remaining 40% for the execution elements such as laser or other, sensor, communication and localization systems.

COMPUTER VISION SYSTEM

The development of computer vision is based on the research, use and testing of various available algorithms and the training of systems based on deep learning technology in combination with standard methods from the field of computer vision. Deep learning has been used for plant disease detection and weed identification and has shown great success in many specific cases (Shin et al. 2016; Kamilaris et Prenafeta-Boldu, 2018; Zhang et al., 2023; Moura Dantas et al. 2023). With this in mind, a large number of different models were created and trained, which were ultimately optimized for application. One of the main challenges was the fact that all processing was to take place live and in multiple layers on the robot itself, with the data obtained being used as the basis for autonomous control, and therefore it must be prepared in such a way that, in addition to the actual recognition, it also contains geometric data necessary for localization, etc. The image processing system was essentially developed for the detection of crops (maize) and weeds (all weeds, i.e. plants that are not crops). Both systems proved to be highly suitable for the tasks at hand and were tested on hardware platforms suitable for mobile use, both in terms of size and power consumption and in terms of an acceptable price, i.e. an economic component. Through the use of computer vision and AI, cRobot achieves a high recognition rate of 87%.

Figure 2. Identifying crops (left) and weeds (right)

AUTONOMOUS DRIVING SYSTEM

Based on computer vision, several methods for introducing autonomous driving have been investigated, some of which are based on the geometric position of the plants found (in perspective), while others are based on finding directions, i.e. planting lines. Both methods were tested on open and closed polygons. It has been shown, among other things, that such an orientation method is in some cases more suitable than a system using RTK-GPS. This is because the different types of GPS methods investigated and tested generally require more expensive systems, meaning that a fleet concept with such systems would not be economically viable. Other methods, such as LIDAR, have also been researched and used as secondary methods and today have great potential for use in agriculture - at an economically acceptable price. The trajectory calculation algorithm generally places much less load on the system than the underlying image processing components, so that it could be integrated into the existing main control system together with others without major challenges and with satisfactory results. Due to the reaction speed and hardware independence, subordinate control systems, which only receive information from the control system, are placed on a lower control level at microcontroller level according to a specially developed concept.

ACTUATORS

Actuators have been the subject of a number of investigations, discussions and tests since the beginning of cRobot development, and in line with the original concept and idea, lasers were the main object of investigation. According to Marx et al. (2012) and Cao et al. (2024), laser dot size and exposure time are two crucial factors for the effectiveness of laser treatment. In addition, Mathiassen et al. (2006) point out that the treatment of weed plants with a CO_2 laser is effective and leads to a 90% reduction in fresh mass, while other laser types have a slightly lower efficiency. In our case, main task was to find suitable laser types that a small autonomous platform could carry, which ultimately ruled out certain laser types and, after extensive trials and testing, established diode lasers as the only possible option for such an application. In addition to laboratory conditions, the lasers were tested in various ways on plants on field polygons, first with a specially developed X-Y platform, then with manual application and finally with a robotic platform. The conclusion regarding the use of lasers in such project environments can be reduced to the fact that the ability to carry only a smaller diode laser affected the average working speed. Considering this fact, it turned out to be crucial to pay attention to the number of robots in the fleet, i.e. the frequency with which a particular spot is visited, as weed growth can be stopped much more efficiently immediately after emergence than in the growth phase when the plant (weed) is already advanced. In view of above, in addition to the laser as the main execution element, other mechanical and chemical methods of weed destruction have also been investigated, which are essentially based on a similar or identical detection methodology, i.e. on the differentiation between the initial plant and the weed and the corresponding orientation of the execution element to the plant in question.

CONCLUSION

Competitive agriculture in the 21st century requires smarter machines and cleaner products; feeding 9.5 billion people by 2050 seems unattainable without state-of-the-art machines and efficient products.

An autonomous robot for weed control on crops can reduce the use of herbicides, improve crop quality of the crop, as well as influence cost optimization and a quick return on investment. In addition, the autonomy of the robotic system is enabled without human intervention. The use of the presented autonomous robot reduces farmers' labour and leaves them free to think strategically and work on investments and production improvements.

We also hope that instead of "driving people out of the field", such systems can help some younger generations "return to the field" with a different character of activities and jobs.

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THE ROLE OF ARTIFICIAL INTELLIGENCE IN MODERN AGRICULTURE

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ABSTRACT

Artificial intelligence (AI) is increasingly finding its way into various areas of the agricultural sector, enabling producers to optimize production processes, reduce costs and increase efficiency. By using big data analytics and advanced algorithms, producers can gain a competitive advantage and drive growth to improve product quality, reduce waste, optimize the supply chain and improve food safety and customer experience. As the industry progresses, further transformative applications of these technologies in food safety and production can be expected, with producers who adopt these technologies increasing their chances of success in this rapidly changing industry.

Although the application of these technologies offers significant benefits, there are certain challenges associated with their implementation. A key challenge is the need for large amounts of high-quality and well-structured data to optimize the algorithms. Food producers need to ensure that the data used by artificial intelligence is accurate, representative and unbiased. This can be a challenge given the complexity and variability of production processes. Another challenge is the cost of implementing the systems and training employees. Developing models and integrating them into existing production systems can be expensive and often requires significant investment in hardware, software and staff who need to be trained to manage these systems and interpret the data generated. Furthermore, there is no one-size-fits-all solution, and each producer must carefully consider its individual needs and goals before investing in the technology.

Key words: *agriculture, artificial intelligence, process optimization, data analytics*

INTRODUCTION

Despite higher productivity, the agricultural sector is facing new challenges. With the increasing realization of the negative impact on the environment, new techniques and approaches should be able to meet the demand for food production while reducing the negative impact on the environment (Sishodia et al., 2020). Understanding management in agricultural processes requires the consideration of a large number of variables and is one of the most difficult areas of statistical quantification. Artificial intelligence in agriculture enables farmers to develop management strategies through "precision agriculture" to maximize results (Linaza et al., 2021). Protected cultivation is characterized by very intensive production on a relatively small area, which requires considerable financial investment, a high labour density and a high crop density per surface area. In addition, a high data density per surface area and time unit is required. Open field cultivation, on the other hand, covers larger areas and generally follows seasonal patterns due to annual production cycles. Digital literacy can vary greatly from farm to farm, so it is crucial to prevent the digital divide from widening, which could lead to an imbalance in negotiating power with producers, suppliers, retailers or other stakeholders. Farm sizes in livestock production can also vary, and this sector faces growing challenges in terms of environmental regulations and greenhouse gas emissions. Water availability and management is a common challenge for all agricultural sectors across world. Key post-harvest activities such as quality assessment, processing, storage and transportation are critical to the entire agri-food sector, with a focus on reducing or avoiding food waste. As a result, advanced, non-destructive methods for monitoring product quality throughout the supply chain are favored in post-harvest technology. The agricultural machinery industry plays a central role in data collection and automation and maintains close links with other industries to develop advanced tools for agriculture. Therefore, scientific and technological innovations are needed to produce a sufficient amount of food (Jung et al., 2021). Artificial intelligence (AI) has been researched for decades and continues to be one of the most interesting topics in modern science. The greatest progress in recent decades has been the invention of search algorithms, machine learning and the integration of statistical analysis into all areas of research (Shaw, 2001). Today, some non-exhaustive examples of AI applications in agriculture are:

- Autonomous driving machines and vehicles,
- Agricultural robots and automated field operations,
- Farming simulation models,
- Soil management, including soil analysis, optimized treatment prescriptions, and soil mapping for specific applications,
- Crop management (e.g., detecting diseases, molds, pests, and applying targeted nutrient solutions),
- Weed and pest control systems,
- Optimization of weather and environmental data inputs,
- Coordination of human labor,
- Animal breeding, feeding, and health management,
- Predictive analysis of various influencing factors,
- Decision support systems,
- Processing, storage and transportation of agricultural products,
- Integration and coordination of all these functions within a single production chain,
- Comprehensive decision support for economic, financial, and organizational aspects of the business.

AI IN FIELD CROP PRODUCTION

When it comes to monitoring plant health, traditional methods are labor-intensive and time-consuming. The use of artificial intelligence is an effective way to monitor and detect potential plant health issues or nutrient deficiencies in the soil. To this end, the combination of drones with ground units (such as autonomous vehicles or robots) is increasingly being used, providing a comprehensive approach to data collection and crop health monitoring. This synergy of technologies allows for more precise and efficient analysis, real-time monitoring and better management of agricultural activities. Deep learning, a subsystem of AI, is used to develop applications to analyse plant health patterns with the aim of understanding soil conditions, the presence of pests and plant diseases. These applications can process large amounts of data faster and more accurately than human inspections, enabling faster detection of potential problems. It is also important to point out that the application of artificial intelligence in agriculture not only relates to the area of problem detection, but also to understanding the causes of these problems, including climatic conditions, soil quality, pest and disease incidence, and fertilizer and pesticide use (Liu, 2020). Through the use of various sensors and technologies, such as satellite imagery or drones, it is possible to collect a wealth of data on the condition of vegetation cover, soil, hydrological conditions and other important parameters. This data provides farmers with information about potential yields and enables them to take appropriate measures to improve their production in good time. Monitoring soil, air and water conditions enables farmers to adopt sustainable farming methods, reduce the need for chemical fertilizers and minimize the negative impact on the environment. In addition, predicting expected yields enables better planning of resources and production management, leading to more efficient use of resources and a reduction in production costs.

AI IN PROTECTED CULTIVATION

Today's high-tech greenhouses are equipped with various sensors to monitor light, temperature, humidity and carbon dioxide, as well as to actively control various execution elements (actuators, electric motors, valves, heaters, etc.) to control all growth factors important for plant production (e.g. lighting, heating, ventilation, cooling, fogging, dehumidification, irrigation and fertilizer dosing) (Hemming et al., 2020). In the context of production processes with large greenhouse areas, the shortage of skilled labour is becoming an increasing problem. The use of AI helps to compensate for this shortage by automating many tasks that traditionally required human intervention. With the increasing demand for high-quality food in urban areas, AI also enables producers to better respond to market needs and optimize production processes to meet demand. AI enables the analysis of correlations between growing conditions and shelf-life processes. This comprehensive approach ensures that production processes in protected areas are aligned with market demand, leading to increased competitiveness and long-term sustainability of the industry.

Timely detection of pathogens and pests is also extremely important. If it is not known what the plant is suffering from, nothing can be done about it. The earlier pests and pathogens are identified, the easier it is to combat them. Therefore, horticultural producers are increasingly relying on automatic detection of pathogens and pests to identify them early and minimize plant damage (Polder et al., 2014). Accurate pest detection requires high-resolution imagery and advanced deep learning techniques. To train deep learning algorithms, a large database of labeled images is required. After collecting the database, the AI is able to distinguish a healthy plant from a diseased plant based on colour changes. There are different types of cameras for recognizing the morphology of plants, the most commonly used being an RGB camera that produces images in the visible spectrum. Such sensors are often used in horticulture for phenotype determination, fruit detection and counting. When producing in protected areas, it can often be difficult to photograph plants from all sides. This can be solved by using more advanced imaging methods, such as a mobile cart system with a mounted camera, drones or a robot equipped with a 3D camera to scan plants. The use of technologies such as chlorophyll fluorescence imaging and thermal imaging shows promising results, especially when applied to different parts of plants, including individual leaves. Image spectroscopy enables a detailed examination of the chemical composition of plants, providing information on pigments, sugars, proteins, fats and water.

AI IN ANIMAL PRODUCTION

In modern livestock farming, various technologies are making it easier and more precise for farmers to manage their production processes. Among the most notable technologies generating data on livestock farms are:

- Farm equipment: Most standard equipment, whether for climate control, automated feeding, or milking, gathers valuable information about animal productivity, energy usage, and overall welfare. Advanced machinery, such as automatic milking systems, can also monitor individual animal health and productivity. The potential to combine these datasets is increasingly recognized, with some companies developing platforms to integrate this information.
- RFID technology: RFID tags, commonly used in supply chain management, are also applied in livestock farming to identify individual animals, verifying their origin throughout the supply chain. These tags can further provide insights into animal health and welfare, though commercial applications remain limited.
- Wearable sensors: Devices such as accelerometers can be attached to animals, typically on their necks or legs, to monitor their behaviour. In the dairy sector, these sensors have been successful in detecting increased activity linked to the onset of oestrus, making them widely adopted. However, their use in other livestock sectors has been less impactful.
- Computer vision technology: Computer vision is gaining importance in monitoring animal health and welfare. Advances in machine learning for image analysis have expanded its potential applications, but this technology is still largely in the research phase, with limited practical success so far.
- Sound monitoring technology: Sound analysis is being explored as a tool to detect signs of compromised animal health and welfare. While much research has focused on analysing animal vocalizations and environmental sounds, most applications remain at the experimental or research farm stage, with few real-world implementations.

AI IN THE AGRICULTURAL MACHINERY INDUSTRY

People, machines, and progress are interconnected: people design and use machines to enhance or simplify life. In this regard, AI represents just another advancement in improving machines, enabling the achievement of production, cost-saving, and quality goals that would otherwise take longer or be unattainable. General AI, which handles personal data and controls access to essential services, is regulated similarly to narrow AI systems, such as those used in the field to safeguard crops. The broad scope of such regulations makes unintended consequences likely, with the machinery sector potentially among the most impacted. As control systems become more intelligent and complex, a growing number of smart systems are being integrated into machinery, often replacing human operators or drivers. With the increasing reliance on features, functions, and services that require connectivity and collaboration, there is a rising demand for secure data sharing and enhanced cybersecurity protocols. For the industry, this necessitates accessing machines via a platform rather than direct access, in order to protect intellectual property, trade secrets, and ensure product compliance.

AI IN THE PROCESSING OF AGRICULTURAL PRODUCTS

The processes of processing agricultural products involve a series of complex steps that require strict control, compliance with regulations and the guarantee of product quality and worker safety. Given the nature of the production process, AI is becoming one of the ways to improve production. In quality control, machine learning models can detect patterns and make predictions by analysing large data sets, which help optimize food quality. In a study conducted by Zhu et al. (2021), the application of deep learning and machine vision in agricultural food processing was analysed. The research results show that the use of machine vision can significantly improve the efficiency of the process, which is crucial for ensuring product quality and safety. Wang et al. (2021) investigated the application of AI for food safety monitoring and prediction. The authors demonstrated high prediction accuracy, suggesting that AI models are a promising method in food processing. There are different losses and inefficiencies in each production line and even in different products in the same line: waste that can occur during the technological process, rejects due to quality defects, variations in size and shape, uneven colour, etc., and the causes of these losses also vary greatly from production line to production line. By detecting variations at the entrance to the production line as well as other factors during production, machine learning models can help identify correlations that may go unnoticed by human observers. AI can be used to analyse the chemical composition of various food ingredients, such as protein, fat and fiber content. This can help to optimize food formulations by identifying the ideal combination of ingredients for a particular species or stage of development. One possible application of AI is predictive maintenance. It goes one step further than preventive maintenance, where equipment is serviced or replaced according to a set schedule. Predictive maintenance involves the continuous monitoring of equipment and the development of its performance profile, which indicates when it is necessary to pay attention to a particular segment of the equipment. The aforementioned models help develop this profile by continuously evaluating parameters such as temperature and vibration. Sensors that monitor the operation of equipment components such as motors, gearboxes, etc. continuously send feedback data that is analysed and used to develop a profile for equipment replacement. However, a predictive maintenance program is neither simple nor easy to implement. It requires specialized knowledge, especially for certain parameters such as vibrations, which are subject to many external variables. For this reason, it is difficult to find failure patterns and further research should focus on developing new methods and algorithms that allow even better results. In terms of controlling working environment conditions, AI can be used to optimize temperature, humidity and airflow in production facilities. Contamination by foreign bodies is one of the main reasons for food withdrawal from the market and rejection by consumers. This type of contamination harms consumers and leads to a loss of loyalty to the manufacturer, resulting in high recall costs. Examples of foreign bodies are insects, glass, metal, rubber and the like. These foreign bodies can accidentally enter the food at any step in the production process. Although the degree of hazard posed by foreign bodies depends on the size, type, hardness and visibility of the body, consuming food containing foreign bodies can lead to choking or certain illnesses (Mohd Khairi et al., 2018). Detecting foreign bodies with the naked eye is difficult. On the other hand, modern technologies and detection methods now enable their easy detection. Examples of such technologies include X-ray imaging, ultrasound, thermal imaging and image and video analysis (Mohd Khairi et al., 2018). These techniques are precise and non-invasive, which makes them acceptable. In addition to detecting foreign objects, AI models can be trained to detect other defects in food mixtures, such as the presence of lumps, and trigger alerts when these anomalies are detected to inform operators of potential problems. When it comes to maintaining hygiene, traditional cleaning systems have often been ineffective. Modern AI-based technologies, on the other hand, use various sensors, such as an ultrasonic sensor, to feed machine learning algorithms with data that can be used to detect contamination and food residues on the equipment. After preparation, the food products are packaged to preserve their quality and facilitate storage and transportation. Non-automated monitoring of food packaging can lead to human error and low efficiency (e.g. mixing of unwanted ingredients in the packaging). These shortcomings can be addressed by using technologies such as machine vision systems, to monitor food processing and packaging. Food manufacturers can use machine learning technology to analyse and identify customer behaviour and needs. The data obtained can then be used to produce "personalized" products that meet these needs and help manufacturers increase their sales.

AI IN STORAGE AND TRANSPORTATION OF AGRICULTURAL PRODUCTS

AI also have some key applications in the storage and transport of agricultural products. For example, AI can monitor and adjust environmental factors such as temperature, humidity and ventilation in storage facilities to maintain crop quality and prevent spoilage. AI-powered systems can predict when storage facilities (e.g. refrigeration units) or transportation vehicles need to be serviced, reducing the risk of breakdowns and ensuring smooth operations. In supply chain management, AI helps optimize logistics by predicting demand, managing inventory and planning efficient transport routes, minimizing delays and reducing costs. In quality control, AI-based image recognition and sensors can automatically detect defects or contamination in stored or transported products and ensure that only high-quality goods reach the market. One of the most important roles of AI is in the field of traceability, where AI systems can track agricultural products throughout the supply chain, increasing transparency and helping to verify the origin and quality of goods, which is important for food safety and certification purposes.

BARRIERS TO ADOPTION OF AI

As artificial intelligence becomes increasingly important in agricultural production, it is crucial to make it accessible to as many users as possible. The main barriers to the adoption of modern digital technologies today are:

- High initial costs: The introduction of AI technologies such as precision farming equipment or autonomous machines requires significant upfront investment, which can be prohibitively expensive for small and medium-sized farms.
- Lack of technical expertise: Many farmers may not have the necessary knowledge and skills to effectively operate and maintain AI systems and require specialized training or support that is not always readily available.
- Accessibility and quality of data: AI systems are highly data-dependent, but many farms lack the necessary infrastructure to collect, store and consistently manage high-quality data, limiting the effectiveness of AI solutions.
- Limited rural connectivity: Poor internet access in rural and remote areas can hinder the use of cloud-based AI solutions and limit real-time data analysis and remote monitoring capabilities.
- Interoperability issues: Different AI systems and farming equipment may not be compatible with each other, making it difficult to integrate different technologies into a cohesive system.
- Resistance to change: Traditional farming practices are deeply ingrained, and some farmers may be reluctant to adopt new technologies because they are sceptical, unsure or afraid of losing control of their farm.
- Ethical and privacy concerns: The use of AI in agriculture raises questions about data ownership, privacy and the potential misuse of personal or agricultural data, which can affect adoption.
- Regulatory challenges: The regulatory framework for AI in agriculture is still evolving, and uncertainties regarding compliance with privacy, safety and environmental regulations may slow adoption.

RECOMMENDATIONS FOR THE USE OF AI IN THE REPUBLIC OF CROATIA

Within the framework of the "Scientific Council for Technological Development and the Scientific Council for Research Infrastructure of Croatia", the Croatian Academy of Sciences and Arts with the "Scientific Centre of Excellence for Data Science and Cooperative Systems" presents a document recommending national characteristics and goals for the use of artificial intelligence in the Republic of Croatia. The document identifies the need to achieve the following goals:

- promote the development of technological and industrial capacities of the Republic of Croatia and the application of artificial intelligence in all areas of the economy and in the private and public sectors;
- prepare society for the socio-economic changes in the Republic of Croatia caused by artificial intelligence;
- ensuring an appropriate ethical and legal framework in the Republic of Croatia for the application of artificial intelligence.

Activities in the field of artificial intelligence in the Republic of Croatia should be coordinated with the digital transformation and an appropriate innovation ecosystem should be built, as the effective application of artificial intelligence is only possible in a highly digitized environment. Digital transformation includes recognizable areas such as cloud computing, the Internet of Things, robotics, digital platforms, distributed business ledgers, cognitive computing and the next generation internet.

CONCLUSION

The use of artificial intelligence in agriculture makes it possible to recognise patterns and solve complex problems in animal breeding, primary production and agricultural food processing. These models offer new opportunities to improve the quality of the final product, taking into account all the factors that influence it. Through this customization, AI provides tools for fast and efficient decision-making, leading to automation and improved efficiency in production. As far as the economic justification for investing in AI technologies is concerned, it is primarily reflected in increasing productivity, improving quality and control of the production cycle and production lines, improving quality and control of the final product, increasing efficiency and simplifying work processes, optimizing energy consumption, increasing technological and managerial discipline, and rapid and complete verification of work and work processes.

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50. ACTUAL TASKS ON AGRICULTURAL ENGINEERING

Original scientific paper

USING SENTINEL-2 DATA AND NDVI TO PREDICT WINTER WHEAT HARVEST

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ABSTRACT

Artificial Intelligence (AI) is revolutionizing how farmers plan for the future their crops. By analysing massive amounts of data from satellites, weather stations, and soil sensors, AI algorithms deliver hyperlocal weather forecasts with unprecedented accuracy, allowing farmers to optimize irrigation schedules, phytosanitary treatments and harvesting times for maximum yield. Sudden temperature swings, heavy rainfall, or conversely, prolonged drought can significantly impact the optimal harvest time. At this time, on a global scale, weather is considered to be a major risk factor for agriculture. Adaptability, innovation, and a very good planning are essential to mitigate the negative impacts of weather and ensure stable and plentiful food production in the near future. This study introduces a hybrid approach to predicting the precise harvesting time for winter wheat, considering grain moisture requirements. The approach leverages high-resolution Sentinel-2 satellite imagery (Level 2A), specifically the Normalized Difference Vegetation Index (NDVI), to analyze vegetation dynamics throughout the growing season. Recognizing the limitations of NDVI alone in determining optimal harvest time, the study incorporates both climate data and reported crop information to develop a robust empirical mathematical model. This model seeks to empower farmers with a more precise and dependable tool for harvest scheduling, ensuring optimal grain quality by integrating spectral data and localized weather forecasts.

***Keywords**: AI application; climate variability; remote sensing; data analysis; harvest optimization.*

INTRODUCTION

This research underscores the significance of integrating modern technologies, such as Sentinel-2 satellite imagery and climatic data, to refine harvest timing for winter wheat, in relation to grain moisture requirements, through the lens of the Normalized Difference

Vegetation Index (*NDVI*). The proposed hybrid approach offers a pragmatic and reliable tool for farmers, contributing to increased efficiency in agricultural operations, particularly for winter wheat harvesting.

Nowadays concepts of Artificial Intelligence (*AI*), Deep Learning (*DL*) and Machine Learning (*ML*) are becoming increasingly well-known across numerous fields. They have been integrated into various domains, including atmospheric sciences (Dewitte et al., 2021), remote sensing (Janga et al., 2023), agriculture (Oliveira et al., 2023), healthcare (Hirani et al., 2024), finance (Goodwell et al., 2021), transportation (Bharadiya, 2023), retail (Goti et al., 2023), manufacturing (Gao et al., 2024), education (Wang et al., 2024), energy (Entezari et al., 2023), entertainment (McCarthy, 2024), telecommunications (Balmer et al., 2020), human resources and many others domains.

Weather predictions have played a critical role across different epochs, significantly impacting societies and economies. The ability to predict weather patterns has evolved from rudimentary observations to sophisticated technological models, reflecting the increasing complexity of our interactions with the environment. Artificial Intelligence (*AI*) and Machine Learning (*ML*) algorithms can analyze vast amounts of data from various sources, including historical weather patterns, current atmospheric conditions, yield forecast and real-time information from Internet of Things (*IoT*) devices (Song et al., 2022). This capability enables meteorologists to identify complex patterns and make highly localized predictions. As a result, weather forecasting is now more responsive, employing deep learning models for predicting the weather (Abdulla et al., 2022).

In the study conducted by Olivetti and Messori (2024), the authors provide a comprehensive review of the latest advancements in deep learning methodologies applied to weather forecasting. They critically assess the challenges that extreme weather events present to contemporary deep learning systems. The paper articulates the imperative for the customization of data-driven models to enhance their efficacy in predicting extreme weather phenomena and proposes a foundational workflow for the development of such tailored models. The data-driven models can be successfully used by the farmers to optimize irrigation schedules, phytosanitary treatments and harvesting times for maximum yield (Younes, 2024).

In the context of agriculture, the impacts of abrupt temperature fluctuations, excessive precipitation (Song, 2019), and extended drought conditions (Chen et al., 2024) on the harvesting of winter wheat illuminate the inherent vulnerabilities of contemporary agricultural systems in relation to climate change. A comprehensive understanding of these phenomena, coupled with the implementation of innovative risk mitigation strategies, empowers farmers to foster more sustainable and resilient food production systems. As climate variability persists in presenting challenges to agricultural practices, it becomes imperative to adopt proactive interventions to safeguard crop yields and promote global food security.

The key index used in this research is The Normalized Difference Vegetation Index (*NDVI*). *NDVI* has undergone substantial evolution since its inception by Rouse et al. (1973), establishing itself as a fundamental instrument within the realms of remote sensing and agricultural research. *NDVI* utilizes the spectral reflectance properties of vegetation, particularly in the red (*R*: 620-670 nanometers) and near-infrared (*NIR*: 841-876 nanometers) wavelengths, to quantify vegetation greenness. The index is calculated using the formula:

$$NDVI = \frac{NIR-R}{NIR+R} \quad \textbf{(1)}$$

Its advantages – namely, user-friendliness and robust correlations with indicators of vegetation health – render it a valuable tool for agricultural or even environmental monitoring. However, it is imperative that researchers remain cognizant of its intrinsic limitations. Recognizing these shortcomings is essential for the effective utilization of *NDVI* in agricultural studies. Moreover, ongoing advancements in remote sensing technologies and methodologies are anticipated to enhance the utility of the *NDVI* in forthcoming research endeavors. As the demand for precise and comprehensive assessments of vegetation continues to escalate, the evolution of *NDVI* is poised to play a crucial role in tackling the challenges arising from global environmental changes.

In the context of agricultural research, grain moisture content emerges as a critical factor influencing both the quality and yield of winter wheat (*Triticum aestivum*). The moisture content of harvested grain serves as an essential indicator of crop maturity, affects post-harvest handling (Risius et al., 2017; Sangha et al., 2024), and impacts the overall storage and marketing strategies employed by farmers.

MATERIAL AND METHODS

Experimental site

This study was carried out over a single agricultural season due to the rotational nature of winter wheat as a crop. As illustrated in *figure 1*, the experimental plot is situated in Iași County, Romania, located in the northeastern part of Europe, specifically at the "Ion Ionescu de la Brad" Ezăreni Student Practice and Research Station.

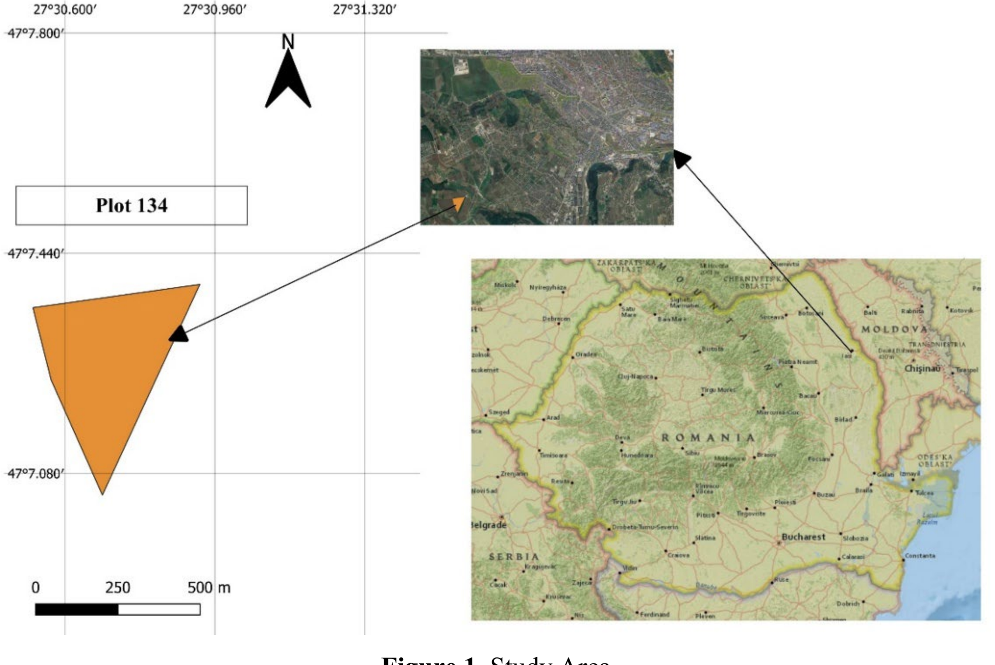

Figure 1. Study Area

The winter wheat cultivation for the selected varieties, Abund C1 and Glosa C1, was carried out over the period of October 13-14, 2023, with a seeding rate of 180 kg ha^{-1} applied to both varieties. For soil fertility, a base fertilization with Eurocereal 10:24:0 was implemented at a rate of 200 kg ha^{-1}. In the spring, a supplementary application of ammonium nitrate was performed, with a dosage of 170 kg ha^{-1} to enhance nitrogen availability. Herbicide treatment was conducted using Sekator Progress at a rate of 0.15 l ha^{-1} to manage weed populations effectively. For pest and disease control, the first treatment (T1) involved the application of Decis Expert 100 EC at a rate of 75 ml ha^{-1} combined with Tilmor fungicide at 1 l ha^{-1}. As a second fertilization, Sulfammo was applied at a rate of 150 kg ha^{-1} to further support plant growth. The second treatment (T2) included another application of the insecticide Decis Expert 100 at 75 ml ha^{-1} to ensure effective pest management.

Data collection

Satellite data collection

The Sentinel-2 data employed in this study were obtained from the Copernicus portal, a European initiative supported by the European Space Agency (ESA), dedicated to providing comprehensive Earth observation data for environmental monitoring, agricultural research, and related studies. Due to potential inaccuracies in satellite data under high nebulosity conditions, only days with less than 2% cloud cover were considered for analysis throughout the growing season. Atmospheric correction was applied using the Sentinel-2 Level 2A (S2L2A) data collection.

Meteorological measurements

Throughout June 2024, prior to the harvesting period of winter wheat, a portable ATMOS-41s (METER-Group, Pullman, WA, USA) weather station was installed at a height of 1 meter above ground level to monitor the local microclimate.

Grain moisture measurements

Starting with 15^{th} of June 2024, the determination of winter wheat grain moisture was conducted using the Granomat V1.0 (Pfeuffer GmbH, Kitzingen, Germany), a precision moisture meter specifically designed for rapid and accurate analysis of grain moisture content. The process involved placing a representative sample of winter wheat into the device, which utilizes a high-frequency oscillation method to measure moisture levels.

Statistical analysis

For the Sentinel-2 data utilized in this study, the Copernicus portal offers comprehensive statistical information, facilitating access to a wide range of datasets and analyses relevant to this study, including standard deviation (SD - σ).

For the meteorological measurements, the data were interpreted in their intrinsic context, as the recorded values fell within the calibration range of the ATMOS-41s weather station.

For the winter wheat grain moisture measurements, random errors or imprecision of measurement were quantified computing standard deviation (SD - σ) of repeated measurements.

$$\sigma = \sqrt{\frac{\sum_{i}^{n}(x_i-\mu)^2}{n}} \quad \textbf{(2)}$$

where:

σ – standard deviation;

n – the number of data points in a data set;

$\sum_i^n -$ the total of all data values;

x_i – the difference between each individual data point;

μ – the sum of all of the data divided by the size.

This formula (2) provides a statistical measure of the spread of data points in a dataset around the mean, helping to understand the variability and consistency of the grain moisture measurements.

RESULTS AND DISCUSSION

The findings of this research demonstrate a significant alignment with existing studies conducted by other researchers in the field of agricultural monitoring. Specifically, the analysis of the *NDVI* throughout the growth stages of winter wheat corroborates several key observations reported in the literature (Yue et al., 2024).

Variability of the Normalized Difference Vegetation Index (NDVI)

The graphic presented in *figure 2* illustrates the fluctuations in the Normalized Difference Vegetation Index (*NDVI*) values over the growing season of winter wheat. The *NDVI* is a key indicator used to assess vegetation.

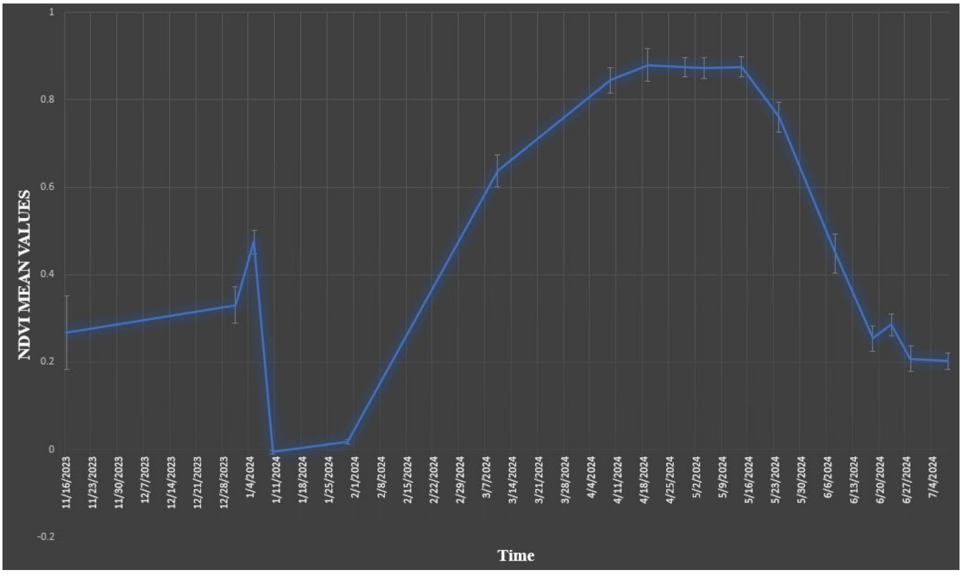

Figure 2. Variation of the NDVI throughout the growing season of winter wheat

The x-axis represents the timeline of various growth stages of winter wheat, while the y-axis denotes the mean *NDVI* values. The graphic illustrates a general increase in *NDVI* during the early growth stages, indicative of healthy vegetation development, peaking at a value of 0.8795 with a standard deviation of 0.0371, observed at crop maturity on April 19, 2024. Significant fluctuations in *NDVI* throughout the season are attributed to heavy snowfall in January 2024, which resulted in mean *NDVI* values dropping below zero, -0.0055 with a standard deviation of 0.0387 on 10th of January 2024. A notable variation occurred on June 24, 2024, when the *NDVI* value unexpectedly increased from 0.254 on June 18, 2024, to 0.286, despite the anticipated downward trend. If compared to the results presented in *figure 3*, it is evident that rainfall occurred on June 22, 2024, of 5.3 l m^{-2} which likely influenced the *NDVI* values observed.

Meteorological Results

Among parameters measured by the ATMOS-41s weather station, only the mean values of the air temperature, wind speed, relative humidity and the precipitation levels were specifically selected for analysis.

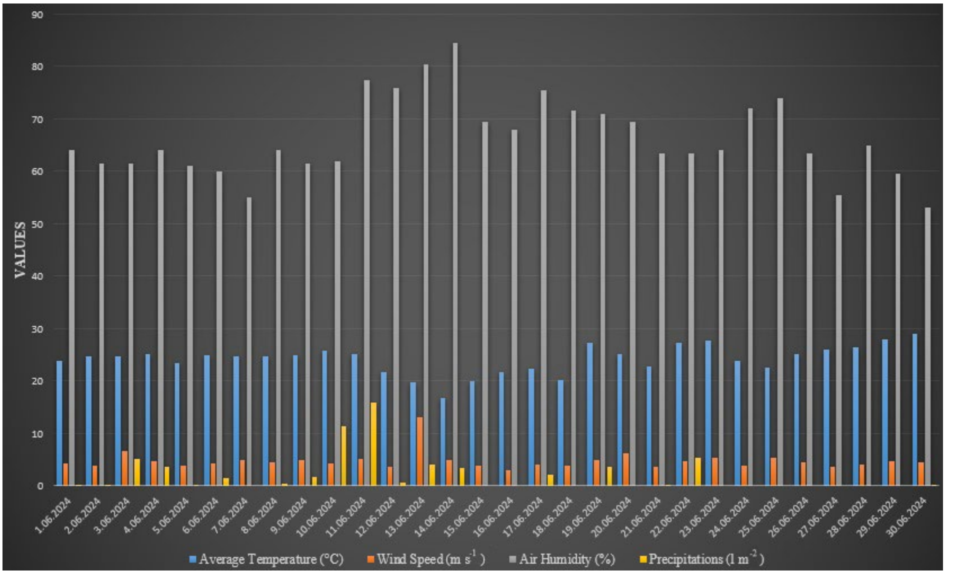

Figure 3. Meteorological parameters from the ATMOS-41s weather station

According to the information presented in *figure 3*, the average temperature fluctuated throughout the month, with mean values ranging from a low of 16.8°C on June 13 to a peak of 29.1°C on June 30. The temperature of 23.9°C suggests generally warm conditions that not only promote crop growth but also facilitate crop maturity. Wind speed varied significantly during June, with mean values ranging from 2.91 m s^{-1} on June 15 to 13.0 m s^{-1} on June 11. The average wind speed throughout the month was approximately 4.54 m s^{-1}, suggesting moderate wind conditions that could impact evapotranspiration rates. Precipitation data revealed significant variability, with the highest recorded rainfall of 15.9 l m^{-2} on June 11. Cumulatively, the recorded rainfall indicated periods of wet weather that could enhance soil moisture levels; however, these conditions may also raise concerns regarding the quality of winter wheat grains, particularly in relation to grain moisture content.

Grain Moisture Results

The mean values of winter wheat grain moisture are depicted in the graph shown in *figure 4*.

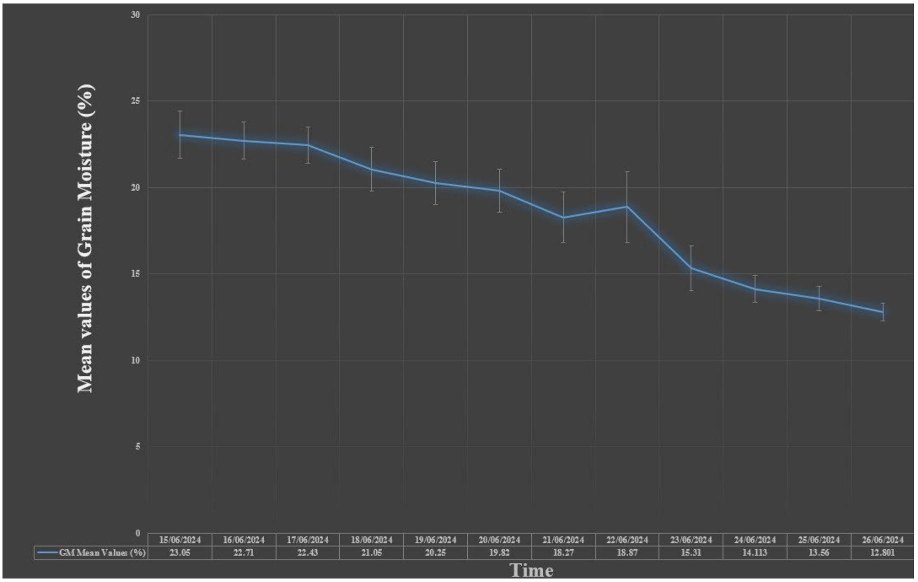

Figure 4. Mean values of the Grain Moisture from the Granomat V1.0 moisture meter

The dataset presents daily measurements of winter wheat grain moisture from June 15 to June 26, 2024, with values ranging from 23.05% to 12.801%. The mean grain moisture values show a declining trend over this period, indicating a possible decrease in moisture content as the harvest approaches.

The standard deviation values, which range from 2.05% to 0.50%, reflect the variability in grain moisture measurements across the days. The notably high standard deviation of 2.05% observed on June 22, 2024, indicates significant fluctuations in moisture levels on that date, as illustrated in *figure 3*. This variance can be attributed to the recorded precipitation of 5.3 l m^{-2}, which likely affected the moisture content of winter wheat grain. In contrast, lower standard deviation values, such as 0.50% on June 26, indicate a stable and uniform consistency in moisture levels as the data approaches the harvest period.

The analysis of *NDVI* values in relation to winter wheat grain moisture revealed a strong correlation between these two factors. As the winter wheat crop approaches maturity, both *NDVI* and grain moisture demonstrate a linear decline. Additionally, it was found that both parameters are influenced by precipitation levels.

To accurately predict harvest time using *NDVI*, particularly when its values show a downward trend due to crop desiccation, it is essential to incorporate correction coefficients or specific intrinsic values that must be collected or simultaneously predicted using *AI*-driven weather forecasts. The formulation can be expressed as follows:

$$T_h = (NDVI^2 * 100) + \sqrt{\omega} + \left(1 - \frac{1}{\sqrt{A_h}}\right) - \left(1 - \frac{1}{\sqrt{v}}\right) - \left(1 - \frac{1}{\sqrt{\theta}}\right) - (\varepsilon) \quad (3)$$

where:

T_h - represent the time, in days, till harvest;
$NDVI$ – represent the value of the Normalized Difference Vegetation Index;
ω – is a coefficient for precipitation levels and could be represented as a specific value;
v – is a coefficient for wind speed and could be represented as a specific value;
θ – is a coefficient for temperature and could be represented as a specific value;
A_h – is a coefficient for air humidity and could be represented as a specific value;
ε – error term, having the value of 2.5, accounting for other unmeasured factors (bioactivity, sunlight, evapotranspiration rates, solar radiation, soil temperature, soil quality and nutrients level, soil compaction, pests and diseases, weed control, etc.).

If the T_h values are negative, it indicates that the harvest time was supposed to have already occurred. This mathematical model is validated for winter wheat within a specific microclimate context and is formulated independent of measurement units, emphasizing the relationships between variables rather than their dimensional attributes.

CONCLUSION

The Copernicus platform, developed by the European Space Agency (ESA), is freely accessible, promoting public engagement and enabling users to leverage advanced Earth observation tools for diverse applications, particularly in agriculture. Additionally, various free weather forecasting services can accurately predict conditions for up to 30 days, which is essential for agricultural planning and helps farmers make informed decisions and anticipate harvest times.

Utilizing the insights from this article, researchers and practitioners can enhance methodologies for predicting winter wheat harvest times by integrating advanced weather forecasting services that harness *AI* and *ML* techniques. This approach fosters the Digitalization of Agriculture and fosters Precision Agriculture principles.

While this mathematical model demonstrates utility, its limitations, particularly concerning *NDVI* values derived from satellite observations and the four-day revisit frequency of the Sentinel-2 satellite, highlight the need for further research with appropriate equipment to enhance accuracy and applicability.

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50. ACTUAL TASKS ON AGRICULTURAL ENGINEERING

Original scientific paper

MIXED INTELLIGENT SYSTEM FOR THE PROTECTION OF AGRICULTURAL AND HORTICULTURAL CROPS FROM THE ATTACK OF PEST BIRDS

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ABSTRACT

Agricultural and horticultural productions depend on the occurrence of pests, in addition to insects and rodents, birds cause significant damage to crops, especially in the ripening stage of cereals and especially fruits. Bird attacks are very harmful to farmers because birds attack in large numbers and if there is no deterrent, complete loss of crops is possible, causing significant economic loss to farmers. A number of factors influence the populations of pest birds and the damage they cause, among them the most important are: the characteristics of the crop and the surrounding area, the availability of food, the ripening time and other characteristics of the cultivated variety, temporal and climatic factors, the behavior of reproduction and movement patterns of birds. The solutions for driving away harmful birds are represented by the use of a complex system that randomly or synchronously uses both acoustic deterrents and light deterrents, by developing an operating algorithm depending on the culture, the harmful bird, the weather conditions, the type of sound and its frequency, the intensity and color of the light, the variety of tools used, the exchange between equipment at certain time intervals, to prevent the birds from getting used to a certain type of rejection. Therefore, proper selection and management of repellent techniques can reduce bird strikes and protect crops while reducing environmental impact.

The main objective of this paper is to present an innovative technical solution, represented by an intelligent, mixed, automated system that uses renewable energy sources, digital technologies for the detection of harmful birds and information processing, acoustic and light repellants for scaring birds. The system consists of three component modules: power module, detection module and rejection module. The entire system ensures the protection of crops and can be used in agricultural and horticultural farms with the aim of driving pests from target crops and increasing farmers' production.

This paper aims to present the constructive elements of the intelligent mixed crop protection system, the software operation algorithm for detecting harmful birds and the preliminary results obtained by using the YOLOv8 (You Only Look Once) system in order to identify birds in real time pests from crops (example on crows).

Keywords: *attack, bird; crows; protection crops; mixed intelligent system*

INTRODUCTION

The current increase in the population has determined the increase in the demand for agricultural goods in order to ensure food for mankind. Thus, the development of deep learning techniques as well as the automation of components are of great help for increasing agricultural production. The advantages of using deep learning in agriculture are: soil management, water management, crop management, yield prediction, disease detection, fruit counting, and weed detection (Albahar M.A, 2023).

Research in the field of bird species identification and classification is a challenge because both their diversity in certain landscapes and environmental changes can lead to improper identification. The large number of birds and the diversity of bird species are important indicators of monitoring target areas with birds in field studies, therefore there are some limitations in the data collection process. Three of these are:

- birds have large habitats, and by observation it is difficult to monitor them;
- qualified personnel (ornithologists) are needed for an exact identification of the birds;
- monitoring birds is expensive because they randomly change their place.

Computer vision and deep learning technologies are up-to-date, effective, significantly reducing the effort and resources needed in the field for bird monitoring, especially in stationary observation areas. Convolutional neural network classification methods include: Faster R-CNN, YOLO, GFL, VGGNet, GoogleNet and ResNet have been applied to bird image classification (Wang et al., 2023).

Many papers present deep learning techniques such as Convolutional Neural Networks (CNNs) which help to successfully identify bird species either from images (Dharaniya et al., 2022; Sivaranjani et al., 2023;Yoshihashi et al., 2017; Rath et al., 2022; Dave et al., 2023; Shetty et al., 2023), or sounds (Eichinski et al., 2022; Stowell et al., 2019; Indumathi et al., 2024; Sprengel et al., 2016; Tang et al., 2024).

In the paper (Hong et al., 2019) deep learning techniques were developed that were based on images of birds in different habitats collected with the help of a drone. Bird detection models were created based on the dataset, such as: Faster Region-based Convolutional Neural Network (R-CNN), Region based fully convolutional network (R-FCN), Single Shot MultiBox Detector (SSD), Retinanet și You Only Look Once (YOLO). The results showed that Faster R-CNN is the most accurate and YOLO is the fastest.

The results obtained in different specialized works based on data sets with common bird species globally and images with manually identified (annotated) birds, different accuracies were obtained depending on the applied learning model, as follows: with Yolov8 maximum accuracy 94 .3% (mAP), (Dave et al. 2023) with Faster R-CNN and Cascade R-CNN average accuracy 73.7% (mAP), (Wang et al., 2023).

The paper (He et al., 2016) presents object detection on PASCAL and MS COCO, the authors adopt Faster R-CNN as the detection method and improvements of replacing VGG-16 with ResNet-101. Results of precision (mAP) were:

- 73,2% on the VGG-16 and 76,4% on the ResNet-101 on the PASCAL VOC 2007/2012 test sets using baseline Faster R-CNN.
- 41,5% on the VGG-16 and 48,4% on the ResNet-101 on the COCO validation set using baseline Faster R-CNN.

In another paper (Fan et al., 2020) bird detection results based on Faster R-CNN of extraction model VGG-16 were 78,4-86,2%.

The present work presents from a constructive, technical and automatic point of view a mixed intelligent system intended for the protection of agricultural and horticultural crops against the attack of harmful birds, provided with a dedicated software that can identify and monitor the activity of crows in a target area.

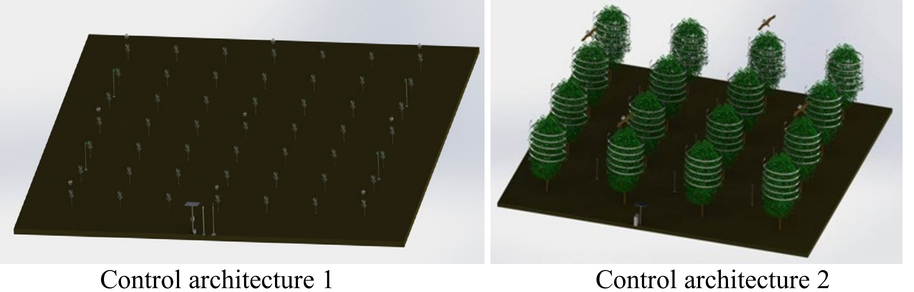
MATERIALS AND METHODS

The intelligent mixed crop protection system has two different control architectures and can be used on agricultural farms to repel pests from target crops and increase farmers' production.

The mixed system for the protection of different crops (agriculture, orchards, vineyards) represented schematically in figure 1 is an experimental model that uses renewable energy sources, digital technologies for detecting harmful birds and processing information, acoustic and light repellants for scaring birds.

The system consists of three component modules: power module, detection module and rejection module:

- The power supply module consists of: solar panels, solar panel system controller, battery and inverter;
- The detection module consists of bird movement detection sensors, smart camera and/or central computer;
- The repulsion module consists of various repelling devices, acoustic and light, which work on different principles: sound generator, ultrasound generator, laser, kites, balloons, reflective tape.



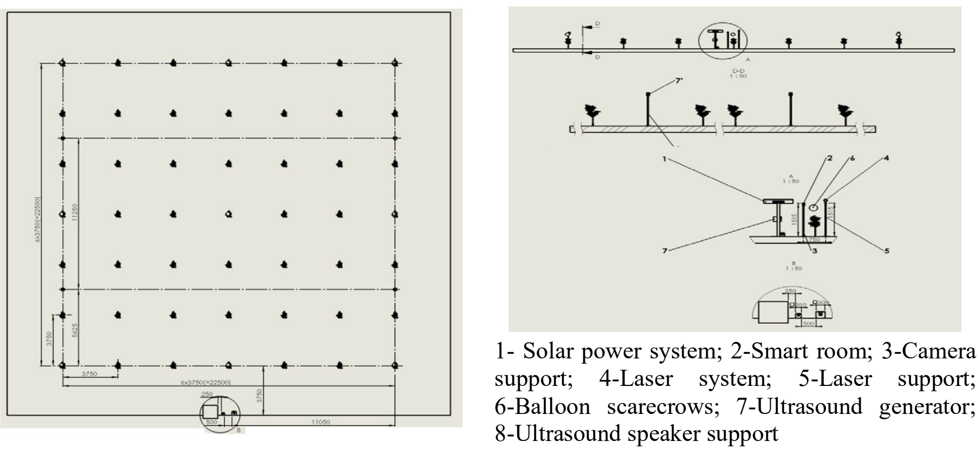
Control architecture 1 Control architecture 2

Figure 1. Intelligent mixed system of agricultural crop protection

The mixed intelligent system for the protection of agricultural and horticultural crops includes two control architectures: *Control architecture 1* and *Control architecture 2.*

Control architecture 1, represented schematically in figure 2, is composed of the following main elements: solar power system, smart camera, camera support, laser system, laser support, balloon scarers, ultrasound generator, ultrasound speaker supports.

The solar power system has the role of providing the electricity needed for the crop protection equipment, such as: the laser system, the motion sensors, the ultrasound generator, the bird of prey sound generator and the actuators. The solar power system consists of the following elements: solar panel, solar controller and solar battery.



1- Solar power system; 2-Smart room; 3-Camera support; 4-Laser system; 5-Laser support; 6-Balloon scarecrows; 7-Ultrasound generator; 8-Ultrasound speaker support

Figure 2. Control architecture 1

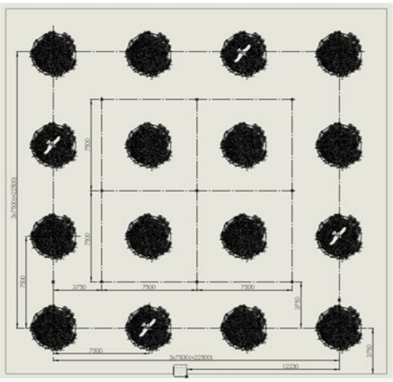
The Neon – 203 B-JNX smart camera, with 2M image resolution, is designed to monitor the target area, rotating at 3600 so as to cover the entire surface of the target area and detect birds from all directions, using deep learning methods based on of artificial intelligence algorithms such as supervised neural networks, using collections of images of pest birds in different poses for training. The camera is supported in the field by a support.

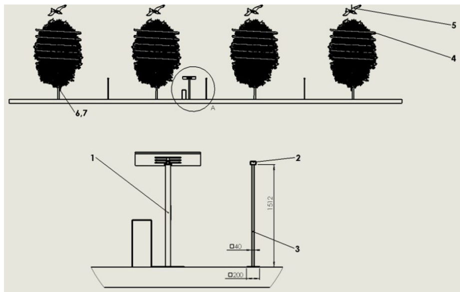
Camera support, supporting the camera in the agricultural area of the experimental area. It represents the supporting element of the room, giving rigidity and stability to the entire construction. It is a welded sub-assembly made of square section pipes and sheet steel.

Laser system, multi-colored (green - with the wavelength of the beams of 532 nm; red - with the wavelength of the beams of 650 nm), acts against birds using laser diodes class 3R, with powerful rays of 50-100 milliwatts (mW). To prevent the birds from getting used to the laser, the laser beams change color and direction constantly. The laser is supported by a support. *Balloon-type scarecrows* are made of plastic, resistant to high temperatures and humidity. Two bright hawk eyes are drawn on them to help scare the birds and they move in the wind imitating birds of prey, reflecting the light so that the birds are intimidated and driven away from the target area.

The ultrasonic generator has 4 speakers, with the ultrasonic acoustic spectrum in the 15-25 kHz range, the acoustic power being between 95-102 dB up to a one meter source. The four loudspeakers are placed in the field on some metal supports, at different distances depending on the surface of the protected area and the range of action of the sound waves so that the entire perimeter is covered.

Control architecture 2, represented schematically in figure 3, it consists of the following main elements: solar power system, motion sensors, sensor support, central computer, holographic tape, kite, sound generator and supports for sound speakers.





1- Solar power system; 2 Motion sensors; 3 Sensor support; 4 Holographic tape; 5-Kite; 6-Sound generator; 7-Sound speaker support

Figure 3. Control architecture 2

The solar power system is the same as in Control architecture 1, consisting of: solar panel, solar controller, battery and inverter.

Motion sensors placed on the supports, at distances of approximately 5-8 m, one to the other, with a role in detecting the presence of birds in the area to be monitored.

The holographic tape is bright and has the role of producing light reflections, extremely disturbing for birds.

The kite can be soared a few meters above the target area with a special string equipped with rotating rings, to ensure a more natural flight, imitating the hawk, a bird of prey that scares away harmful birds from agricultural and horticultural crops.

The sound generator, fixed on the support, is made of hard materials that make it resistant to the weather. It is equipped with a speaker whose volume can be adjusted, the sound emitted by a predatory bird (eagle, hawk, owl, owl) and the sound playback mode (random, sequential) can be chosen. The sonic frequency is between 3-5 kHz and the sound propagation has acoustic powers between 105-110 dB, the sounds emitted are not acoustically disturbing to people.

The operating principle of Control architecture 1 is as follows: the detection module formed by the smart camera continuously monitors the target surface and if the bird is detected, the rejection mode is activated, by turning on the laser and/or the generator with ultrasonic sound waves of different frequencies.

The working principle of Control architecture 2 is as follows: motion sensors will detect the movements of birds in the target area and transmit the data to a central computer which will activate the repellent module, which triggers a certain repellant frequency and a certain sound, so that the birds will they will move away from it, or one of the other repellents, the holographic tape or the kite, will act.

The algorithm of operation of the software for the detection of harmful birds (in our case, crows) was designed to perform periodic checks in a specific area. In the first stage, the collected images or data are analyzed to detect the presence of birds. If birds are detected, the algorithm initiates a continuous check to monitor their presence constantly. As the time spent by the birds in the monitored area increases, the algorithm identifies their stable presence. At this moment, a bird scaring system is activated. This action is random to prevent the birds from learning and becoming accustomed to a specific sequence.

In our research, the YOLOv8 (You Only Look Once) system was used to identify crows in real time. After one or more crows have been identified, the program sends, after 30 seconds, a digital signal to an Arduino system. It further activates the systems (laser, sound and/or ultrasound) used to repel crows. Figure 4 shows the running time for the software operation algorithm for the detection of pest birds in crops.

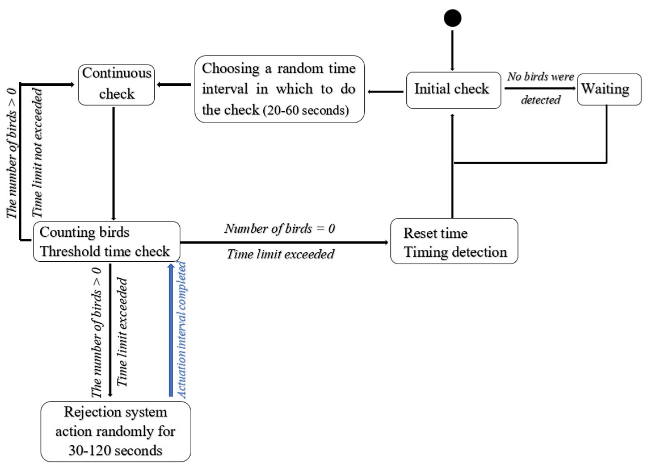


Figure 4. The duration of time required for the operation of the mixed intelligent system for the protection of agricultural and horticultural crops

RESULTS AND DISCUSSION

Preliminary results of the training process of dedicated software for the identification of crop pest birds (Crows case study)

The parameters of the confidence threshold for the YOLOv8 model used in the program to identify crows are shown in table 2. The confidence threshold of the prediction has values from 0 to 1 and the F1 score is the harmonic mean of precision and recall. In order to evaluate the performance of the developed model, it was appreciated that: a higher confidence threshold means that only predictions with higher confidence scores are considered valid and the F1 Score provides a unique measure that balances both precision and recall. The results in the table 1 indicate that the F1 score changes as the confidence threshold increases

Table 1. The parameters of the confidence threshold of the prediction versus the score F1 for Yolov8

Confidence threshold	0.0	0.2	0.4	0.6	0.8	1.0
F1 score	0.18	0.32	0.49	0.54	0	0

Analyzing the data in table 2, it is found that both the confidence threshold and the F1 score increase from 0 to 0.6, indicating a good performance between these values. At confidence thresholds greater than 0.6, the F1 score drops sharply to 0, suggesting that higher thresholds may remove too many predictions, significantly reducing recall.

Precision, recall, mAP (mean Average Precision) and F1 score are essential metrics for evaluating the performance of a machine learning (ML) model. Precision indicates the proportion of correct positive predictions to the total number of positive predictions made by the model, reflecting the accuracy of the model's detections. Recall (sensitivity) measures the proportion of positive cases correctly identified by the model over the total number of true positive cases, demonstrating the model's ability to detect all relevant objects. mAP (mean Average Precision) is the average of the precisions calculated at different recall levels and provides an overall measure of the model's performance across all detection classes and thresholds. The F1 score is the harmonic mean between precision and recall, showing a balance between these two metrics and being useful in situations where both precision and model sensitivity are important. These metrics are critical to understanding and optimizing model performance.

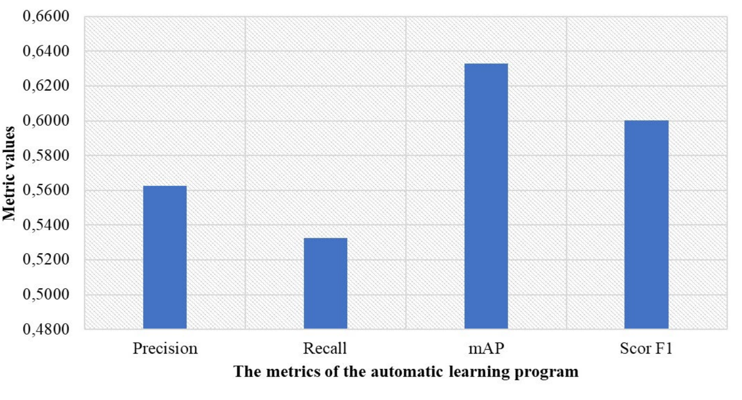


Figure 5. Metrics values from the machine learning model used in the crow identification program

In the images in figure 6, one can see the process by which the program applies a "bounding box" (border) over the objects recognized as crows, with the confidence index of the program varying between 0 and 1. In the left part of figure 6, you can see raw images (with unlabeled crows), and on the right side, images after applying the crow identification algorithm.

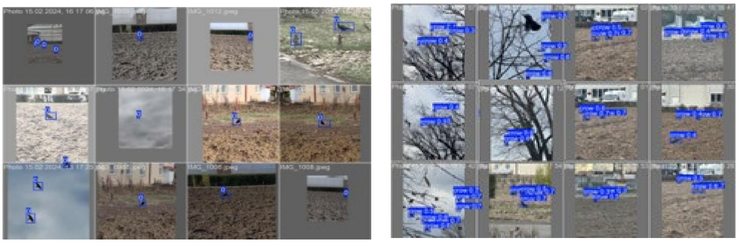


Figure 6 Images before and after applying the crow identification algorithm

A confusion matrix was used to evaluate the performance of a crow classification model. The obtained values are reproduced in table 2.

Table 2 Confusion matrix values for the YOLOv8 model used in crow classification

Prediction	**True positive**	**False negative**
Positive	27	0
Negative	5	0

True positive (TP) shows the number of examples that were correctly classified as crows, in this case there were 27.

False negative (FN) shows the number of examples that should have been classified as crows but were misclassified as "background", in this case, there were 5.

The preliminary results obtained in the training process of the dedicated software for identifying crows, considered harmful birds in crops, showed that the efficiency of the YOLOv8 model in identifying crows has certain limitations, namely:

- the F1 score of 0.60002 indicates a balance between precision (0.56025) and recall (0.53214), suggesting that the model is moderately successful in detecting crows while handling false positives and negatives;
- the mAP (mean Average Precision) of 0.63120 shows the general ability of the model to accurately predict the presence of crows above different confidence thresholds;
- the confusion matrix shows us that the model correctly identified 27 crows and erroneously 5 crows, classified as background, which shows the compromise between precision and recall.
- the parameters of the confidence threshold of the prediction versus the F1 score for Yolov8, indicate the optimal confidence threshold at approximately 0.6, the value at which the model achieves the best F1 score. In the case of practical applications, this selected threshold is valuable in terms of maintaining a balance between detecting true positive predictions and minimizing false detections.

Said et al. (2024) in their study, report that performance metrics for her proposed work (images file contains 20925 labelled images following the YOLOv7 specifications) named ATAN.(attention-based temporal analysis network) and SACN (spatially aware convolutional network): Precision (0.97), Recall (0.96), mAP (0.96) and Score F1 (0.9650) with the identification of 970 birds and 40 erroneous identifications. This recent research has successfully demonstrated the development and implementation of a novel deep learning framework for real-time bird detection. (Suleyman et al., 2021) in their study, report that deep learning for birds' identification system using VGG-19 for extracting features from images (database of this study is contained 4340 images) with PCA (principal component analysis) and ANN (artificial neural networks) showed high classification accuracy (70.9908), precision (0.718), recall (0.71) and F-Measure (0.708) compared to other classifiers.

CONCLUSIONS

Due to the significant impact of pest birds on agriculture, the development of an intelligent mixed agricultural and horticultural crop protection system controlled by specialized software for the detection of pest birds in crops is a vital research area.

From a constructive point of view, the intelligent mixed system for the protection of agricultural and horticultural crops consists of 2 control architectures, each with 3 component modules (supply mode, detection mode and rejection mode). Within the two control architectures, modern, intelligent and energy-efficient devices and equipment were used and a dedicated software was developed for the identification of crows.

During the training process of the dedicated software for identifying crows presented in the paper, the YOLOv8 algorithm identifies crows and monitors their activity, then transmits a digital signal to an Arduino system, which further activates the systems (laser, sound and/or ultrasound) used to repel crows, depending on changes in their behavior or in the surrounding environment, with the aim of maintaining the efficiency and adaptability of the system in the face of different conditions, preventing the habituation and adaptability of the birds to a specific sequence.

In conclusion, although the YOLOv8 model shows good results in the detection of crows, an improvement of the model, through additional training data or by adjusting the optimal parameters, is beneficial in the more accurate identification of harmful birds in agricultural or horticultural crops.

ACKNOWLEDGEMENT

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50. ACTUAL TASKS ON AGRICULTURAL ENGINEERING

Original scientific paper

EVALUATION OF REMOTE SENSING TECHNOLOGIES FOR MEASURING THE ACCUMULATED PRECIPITATION

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ABSTRACT

The best management practices in agriculture targeted on increasing food production, must be mandatory focused on remote sensing and GIS techniques based on satellite results. The present paper is a study realized in Timis County area by comparing the resolution of two systems specialized in measuring and recording the amount of atmospheric precipitation: OneSoil Platform and Meteorological Station Network from CLINSIM Cross-Border Project. Three meteorological stations (located in Timisoara, Cenei and Grabat), randomly selected for measuring the accumulated precipitation in July, August and September 2024. For the same period and places, the quantities of precipitation existing in the database of OneSoil Platform were determined also. The data were segmented on months and days. Information regarding precipitations was statistically processed using Microsoft Excel and Stategraphics Centurion 19. The significance of differences between groups and validity of hypothesis were verified by Fischer Test. Using ANOVA any relationships between position (in field farm, in warehouse of the farm and in the town) and differences between correspondent values were sought, analyzed and explained (causes). The average precision/resolution for OneSoil platform was between 95 to 63%, depending on the absolute value of precipitations. The main conclusion resulting from the study is the use of OneSoil platform in applications of remote sensing of the Earth regarding Precision Agriculture could be strongly recommended, thanks to its capacity and optimal terms and timing of work and cost.

***Key words**: OneSoil Platform, accumulated precipitation, remote sensing, precision*

INTRODUCTION

Today, digital technology, remote sensing, Unmanned Aerial Vehicles (UAVs), etc. are important key tools for monitoring agricultural conditions by providing essential parameters such as: normalized difference vegetation index (NDVI), continuous monitoring and yield prediction using optical signals, and biophysical models (Sishodia et al., 2020; Gao et al., 2020), providing timely information critical for decision making (Franch et al., 2022; Cintas et al., 2023), etc. So that farmers and agricultural managers, by analyzing remote sensing data, can make informed decisions about interventions in a lot of agricultural technologies such as: irrigation, fertilization, pest control, etc. (Shi et al., 2019). An important solution, as several studies have already demonstrated, is the utility of freely and commercially available satellite data for field-scale monitoring (Kalecinski et al., 2024). Directly or by dedicated platform (example „precision farming platform OneSoil"(OneSoil, 2024)), the satellite Sentinel-2, thanks to high quality images, is frequently used to assess conditions and vegetation indices for estimate yield at the field conditions (Hunt et al., 2019), inclusive for analysis of low-pressure tires in the cultivation technologies (Truflyak et al., 2022). Despite these possibilities, even the significant potential to improve management strategies, there is a gap in the literature regarding the applications of remote sensing data in agriculture, excepting few extensions, example the use of UAVs for image capture (Lontis et al., 2023; Tucu et al., 2023). The most important problem is the precision of data from remote sensing determined by comparing simultaneously different methods (classic on site and remote) and statistical analysis of precision (Huang et al., 2020; Bota et al., 2020).

The main objective of the present paper was to evaluate the performance (feasibility) of using OneSoil platform satellite and Meteorological Station Network from CLINSIM Cross-Border Project in measuring and recording the amount of atmospheric precipitation, in Timis County area, by random selection of meteorological stations.

METHODS

The succession of methodological steps was created for design the study's workflow included in present paper (figure 1)

The field of experiment was situated in Timis County, in 3 sites, with meteorological stations, included in agricultural farms at Cenei (noted SM1, (45.725408N, 20.206538W, 86.4 m altitude)) and Grabat (noted SM2, (45.882604N, 20.728288W, 94 m altitude)), and last situated at Mechanical Engineering Faculty in Timisoara (noted SM3, (45.745249N, 21.225853W, 85.5 m altitude)) (figure 2). The local climate is classified as temperate continental situated in flat fields, in the influence of Bega River. The base information (data) of this experiment were obtained from the 3 meteorological stations (Pessl, iMETEOS 3.3) parts of the project CLINSIM, having technical specifications (for station generally and rain gauge) presented in table 1. The study period was between 30.06.2024 and 30.09.2024, with daily registration of precipitation.

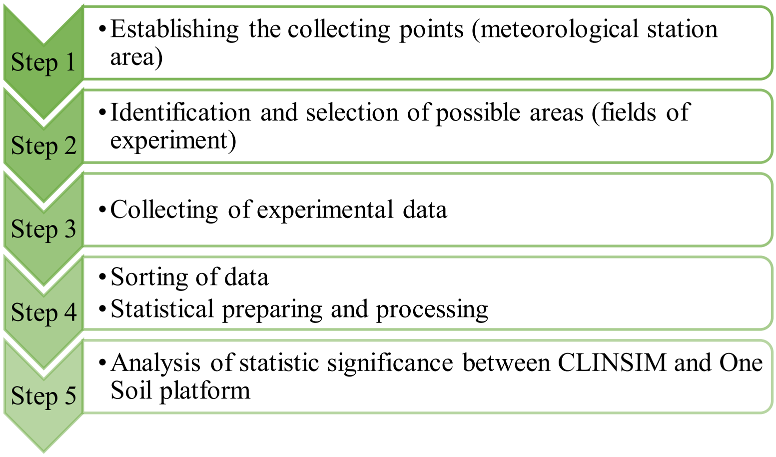

Figure 1. Methodological flow

Table 1. Technical specifications of meteorological stations

	No.	Feature	Value
Meteorological Station iMETEOS 3.3	1	Sensors layout	1 wind speed, 1 leaf wetness, 1 rain gauge, 1 water-meter (reed), 2 hygroclips (air temperature and relative humidity) 5 digital inputs: automatic sensor recognition, supporting sensor chains (max. 600 sensors)
	2	Memory	8 MB flash memory
	3	Dimensions without sensors	41 cm L x 13 cm W x 7 cm H
	4	Weight without sensors	2.2 kg
	5	Battery	Rechargeable 6V, 4.5Ah, Operating range: -35 °C to 80 °C
	6	Solar panel	Dimensions: 13.5 x 13.5 cm, 2 Watt solar panel
	7	Measuring interval	5 minutes
	8	Logging interval	15 minutes
	9	Transmission frequency	60 minutes
Rain Gauge	10	Sensor Type	Double tipping buket rain gauge
	11	Output	Switch signal
	12	Switch	Reed contac, solid state
	13	Sensitivity	1 tip per 0.2 mm or 1 tip per 0.5 mm
	14	Collector Surface	200 cm2
	15	Evaluation	Digital
	16	Maximum Rain	12mm/min
	17	Dimensions	185 mm (diameter) x 250 mm (height)

The experimental plot size was rectangular 8 m x 3 m (24 m^2), according to usual specifications.

For testing the performance of precision farming platform OneSoil the information regarding precipitation taken from OneSoil Yield App – Simple Precision Farming. Collected data were prepared using Microsoft Excel, for statistical analysis by STATGRAPHICS Centurion 19, calculating absolute and relative error (Δa, respectively, Δr):

$$\Delta a = |pOi - SMi|,$$

where:

pOi – indication from OneSoil platform for place i (i=1,2,3- corresponding to the site);

SMi- – indication from meteorological station for place i (i=1,2,3- corresponding to the site),

and:

$$\Delta r = 100\frac{|pOi - SMi|}{\mathrm{pOi}}, [\%].$$

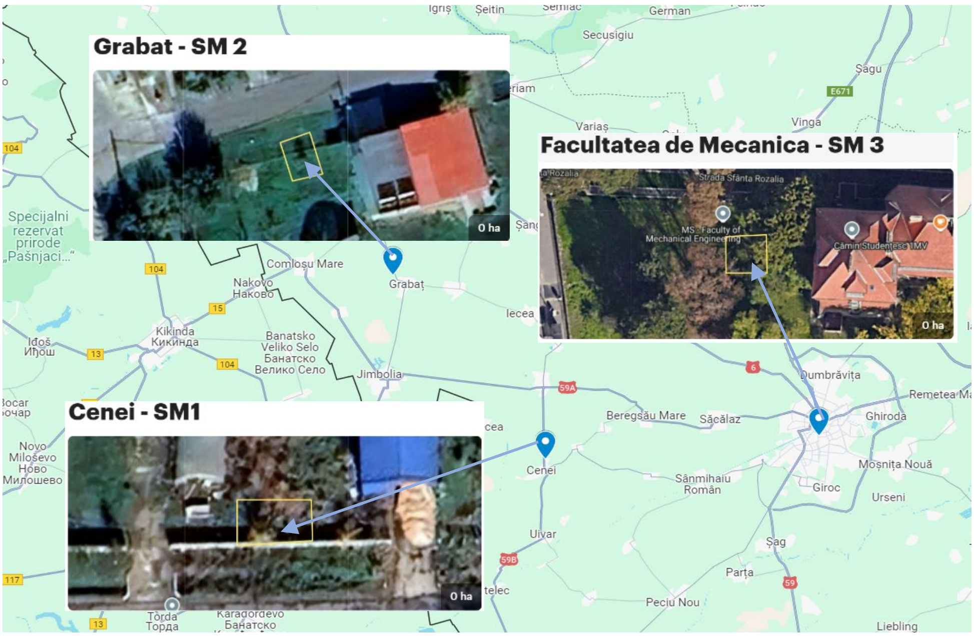

Figure 2. The field of experiment, position of sites (Picture from drone, map from Google)

Statistical relevance was verified Multiple-Sample Comparison by ANOVA, and Multiple Range Tests, if existing influences of station site.

RESULTS

Variation of precipitation quantity pOi (indicated from OneSoil platform for place i (i=1,2,3- corresponding to the site) and SMi (indication from meteorological stations for place i), and relative error, Δri are presented in figures 3,4,5, respectively for SM1, SM2 and SM3.

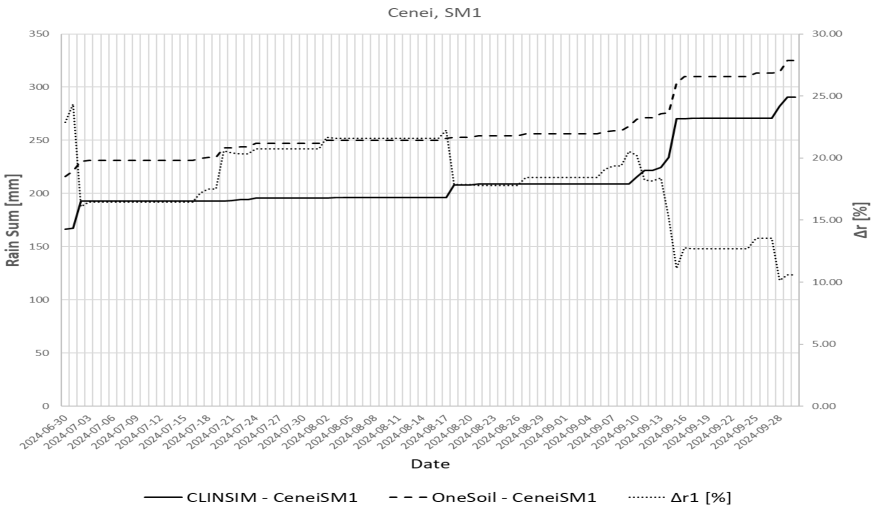

Figure 3. Variation of precipitation quantity for the site SM1, Cenei

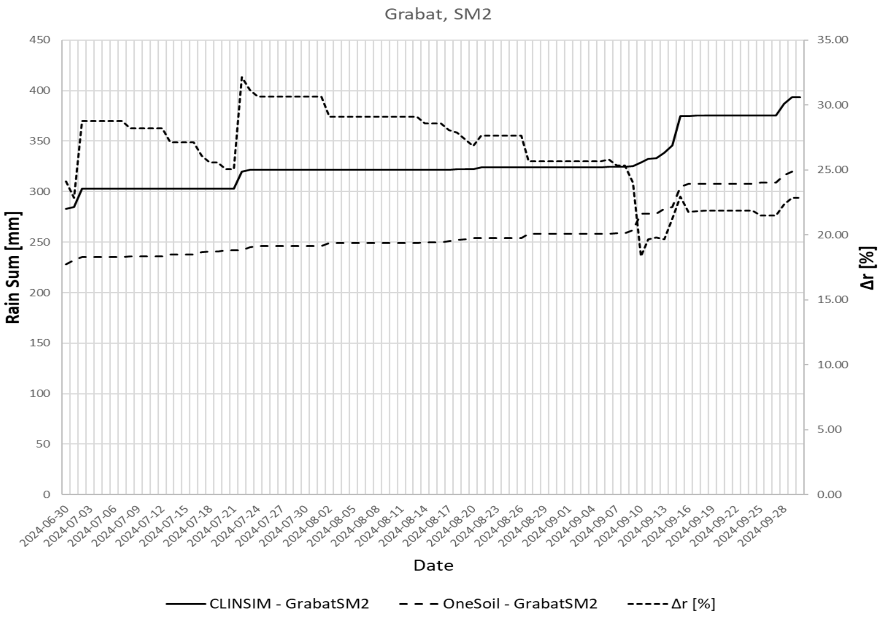

Figure 4. Variation of precipitation quantity for the site SM2, Grabat

Table 2 presents the Summary Statistics results of Multiple-Sample Comparison for Δr1, Δr2 and Δr3, noted, respectively, Dr1 (93 values ranging from 10.13 to 24.34), Dr2 (93 values ranging from 18.35 to 32.15) and Dr3 (93 values ranging from 22.48 to 40.29). Because the standardized skewness and/or kurtosis is outside the range of -2 to +2 for 3 columns, some significant non-normality in the data is present, which violates the assumption that the data comes from normal distributions.

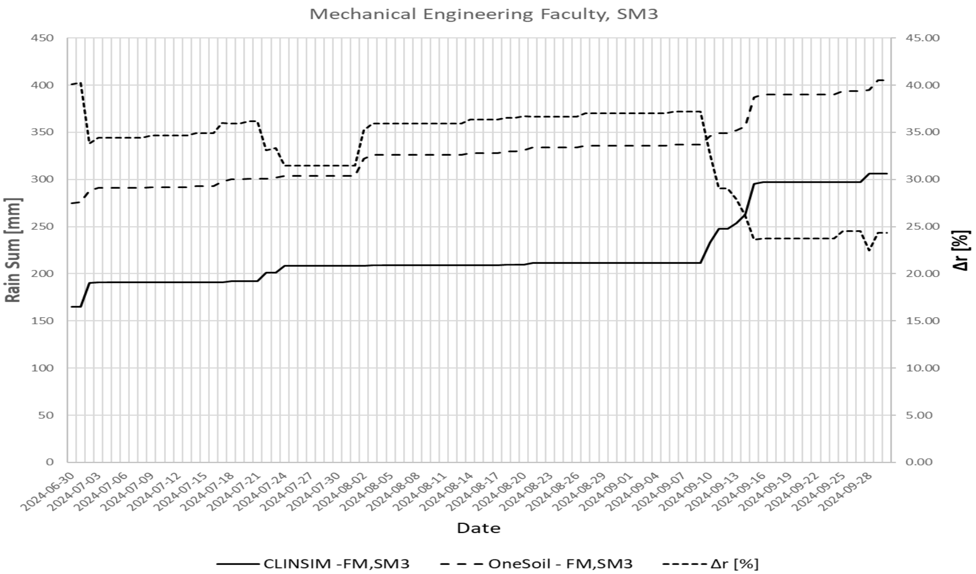

Figure 5. Variation of precipitation quantity for the site SM3, Mechanical Engineering Faculty

Table 2. The Summary Statistics results of Multiple-Sample Comparison

	Count	Average	Standard deviation	Coeff. of variation	Minimum	Maximum	Range	Stnd. skewness	Stnd. kurtosis
Dr1	93	17.97	3.23	17.99%	10.13	24.34	14.21	-2.321	-0.670
Dr2	93	26.39	3.23	12.24%	18.35	32.15	13.80	-2.114	-1.292
Dr3	93	33.18	4.83	14.57%	22.48	40.29	17.81	-4.224	-0.470
Tot.	279	25.83	7.29	28.23%	10.13	40.29	30.16	0.161	-3.344

The results presented in previous figures demonstrate the favorable influence of precipitation` quantity on the relative error, Δri, due to the increasing of the number of rainy days in September.

The results of test for significant differences amongst the Δri means, Analysis of Variance, are presented in table 3. Can be observed the F-ratio, is equal 363.661 and the P-value of the F-test is less than 0.05 (0.0000), so, a statistically significant difference was demonstrated between the means of variables Δri means, at the 95.0% confidence level. It was confirmed that the differences between the place (site) of determination influenced statistically significant the difference relative between the indication of meteorological stations and OneSoil Yield App – Simple Precision Farming platform.

Table 3. The results of test for significant differences amongst Δri means, ANOVA

Source	Sum of Squares	Df	Mean Square	F-Ratio	P-Value
Between groups	10713.80	2	5356.88	363.66	<0.005
Within groups	4065.60	276	14.73		
Total (Corr.)	14779.40	278			

The Multiple Range Tests results for determining which means are significantly different from which others are presented in table 4. By multiple comparison procedure table 4 applies to determine which means are significantly different from which others. Because an asterisk has been placed next to 3 pairs, it indicates that all pairs present statistically significant differences at the 95.0% confidence level.

Table 4. The Multiple Range Tests results

	Count	Mean	Homogeneous Groups	Contrast	Sig.	Difference	+/- Limits
Dr1	93	17.97	X	Dr1 - Dr2	*	-8.42	1.108
Dr2	93	26.39	X	Dr1 - Dr3	*	-15.15	1.108
Dr3	93	33.12	X	Dr2 - Dr3	*	-6.73	1.108

* Denotes a statistically significant difference.

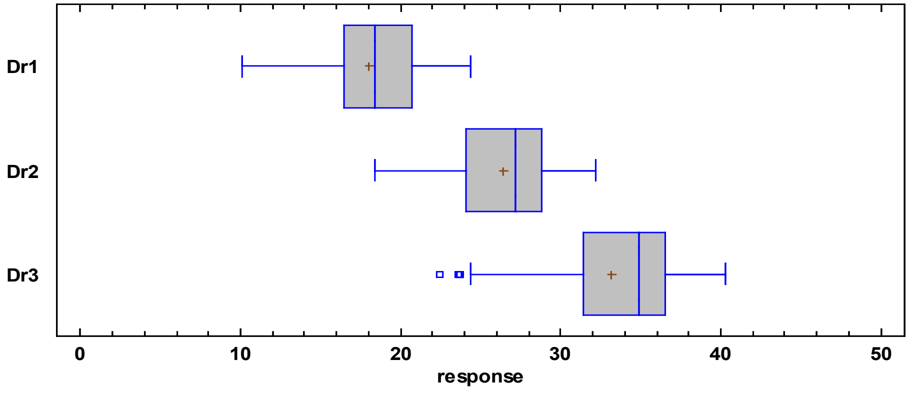

Figure 6. The Box-and-Whisker Plot for relative differences corresponding to the sites

Figure 6 presents the Box-and-Whisker Plot for relative differences corresponding to the sites. It indicates that for the sites situated in field (SM1 is in field), the data regarding precipitation has a precision with more than 80% in about 75% (3 quartiles) of determination. The lowest precision was in the case of determination in urban areas (more than 63% in about 75% (3 quartiles) of determination), at SM3 situated in the town Timisoara, a lot of building around.

CONCLUSIONS

This study demonstrates, by combining innovative information from meteorological stations and OneSoil satellite platforms, the influences of natural surroundings (position in field) and quantity of precipitations on their performed comparably performance. The average precision/resolution for OneSoil platform, expressed by relative error, was between 95 to 63%, substantially influenced by absolute value of precipitations. The main conclusion resulted after study is the use of OneSoil platform in applications of remote sensing of the Earth regarding Precision Agriculture could be strongly recommended in field areas, thanks to its capacity and optimal terms and timing of work and cost (can be used for free). Another recommendation is to carefully use the satellite platform in measuring precipitation inside the town area due to the influences of buildings and trees on the satellite signal (error Multipath).

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50. ACTUAL TASKS ON AGRICULTURAL ENGINEERING

Expert paper

PRECISION FERTILIZATION OF WINTER WHEAT

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ABSTRACT

As part of the EIP Precision Agriculture and Digitization project, an experiment with precision fertilization on a winter wheat crop was carried out on the Štefan Cigut farm. The experiment was carried out on a very heterogeneous area of 11.73 ha. The sowing of winter wheat of the RGT REFORM cultivar was carried out on October 23rd 2023. Pre-sowing soil treatment without plowing in a conservation way was carried out with a circular harrow and a Horsch Pronto seed drill. The area with the wheat crop was divided into two parts, half of the area was fertilized with a variable dose of fertilizer, and the other part of the area was fertilized with a fixed dose of KAN fertilizer in four doses. The preparation of fertilization maps was carried out in the GeoPard Agriculture program. The trial harvest was carried out on July 10th 2024 with a New Holland CR 9060 combine with simultaneous crop mapping. The average yield on the surface with a fixed dose of N fertilizer was 6.749 t ha^{-1}, and the yield on the variant with variable fertilization was 6.716 t ha^{-1}. The yield on both variants of the study was the same. The reason is the comasation in the previous year. The limiting factor for a higher yield was not a lack of nitrogen, but rather a low pH of the soil in individual parts of the surface, the basic supply of soil with phosphorus and potassium, and high soil compaction in individual areas of the field.

Key words: *winter wheat, precision fertilization, N fertilizer, yield, pH*

INTRODUCTION

Innovative technology has changed the way our world works over the past 60 years. Agriculture is also experiencing development, where robotization and modernized technology are gaining ground. Maintaining human needs for food in a world with a global population has been identified as a major challenge for agriculture in the future. How to produce enough quality food?

The beginning of wheat cultivation dates back to the very cradle of human civilization. It began as early as 9.000 to 11.000 years ago in the "Fertile Crescent", along the Euphrates and Tigris river basins. It was in this area that the first forms of cultivated wheat appeared. On the basis of archaeological discoveries of wheat, it was established that the original wheat was a wild type of single-grain mash, which was initially more harvested than cultivated. Somewhere at the end of the seventh millennium, they began to grow wheat. Cultivation of wheat represented the foundation in the further development of civilizations. Around 6000 years BC the wooden plow appeared, expanding the possibility of cultivation. The introduction of a three-field rotation (winter, spring and fodder crops) helped to increase the yield. Kolobar began to be established somewhere at the end of the migration of peoples. In the 17th century, wheat began to spread in America, first from the Atlantic direction, and a century later also towards the Pacific to Mexico and California. The 18th and 19th centuries are characterized by rapid industrialization and the introduction of mechanization into processing procedures. At the same time, the crop rotation improved, and more and more scientific attention was paid to cultivation. Breeding of varieties that yielded much more grain per hectare began gradually. Today, with the help of modern mechanization, wheat yields in certain countries exceed 10.000 kg/ha (Tajnšek, 1988).

Wheat is the most widespread crop in the world, it is covering an area of more than 218 million hectares and occupies almost 30% of grain crops (FAOSTAT, 2024). Low yields have always been associated with biotic and abiotic stresses since approximately direct crop losses due to pests and diseases account for 20 to 40% of world wheat production (Ali et al., 2019).

With continued population growth and increasing demands on water resources, precision conservation will have an increasing role during this new millennium. It has been reported that world population is expected to be about 9.4 billion by 2050, and that increases in crop yields will have to be achieved primarily from land that is currently under production since most of the world's arable land is already being cultivated. These increases in population growth and food and water demands will put increasing pressure for development of new more efficient technology and production practices that contribute to higher yields. Since intensive farming can potentially impact soil and water quality, parallel increases in new practices and technology contributing to improved soil and water conservation practices will be needed to help sustain and maintain the needed yield increases from agricultural systems (Berry, 2003).

Research is lacking on the long-term impacts of field-scale precision agriculture practices on grain production. Following more than a decade (1993–2003) of yield and soil mapping and water quality assessment, a multi-faceted, ‘precision agriculture system’ (PAS) was implemented from 2004 to 2014 on a 36-ha field in central Missouri. Therefore, the greatest production advantage of a decade of precision agriculture was reduced temporal yield variation, which leads to greater yield stability and resilience to changing climate (Yost et al., 2017).

For a good wheat crop, the amount of nitrogen is one of the key fertilization factors. Wheat can take up to 30% more of it than it actually needs. Of course, overabundant meals cause more serious consequences on the crop, so it is necessary to add nitrogen when the plant needs it most, or at most two months in advance. From sowing to the beginning of growth, wheat consumes somewhere between 8 to 22%, and from the beginning of kneeling to flowering it takes in somewhere between 70 to 80% of nitrogen (Tajnšek, 1988).

Nitrogen can be applied with organic fertilizers or mineral fertilizers. Organic fertilizers such as manure, slurries and slurry work very well on the physico-biological properties of the soil, they increase the air permeability of the soil in heavier soils and the ability of the soil to retain water in lighter soils. Barn manure enriches the soil with organic matter, as 10 tons of manure is known to contain somewhere up to two tons of organic matter. With mineral fertilizers, we can more precisely and consistently add individual nutrients that we know are lacking in the soil. Nitrogen mineral fertilizers are mainly available in the form of limestone ammonium nitrate - KAN with a content of 27% and UREA, which contains 46% of nitrogen. The latter form of nitrogen is widely used in the form of foliar fertilization of cereals in the generative phase and when there is a lack of moisture in the soil, because then the movement of nitrogen is the most limited. It is necessary to be careful not to overdo it with UREO, as it can cause blight on the plant, which leads to a decrease in yield or even to the collapse of the plant (Tajnšek, 1988).

Nitrogen monitoring is extremely important for the investigation of many metabolic and structural processes and the optimal ripening of wheat. The element plays an essential role in wheat health. Since nitrogen is not immobilized in the soil and there is no excess of reserved plant nitrogen, fertilization is absolutely necessary during the individual periods of wheat growth (Krishna, 2018).

If nitrogen is low, stunted growth, poorer growth, fading leaves and a small yield occur. Fertilization requirements are greatest near flowering, at which stage plants absorb 80% of total nitrogen. Fertilizing before this period is crucial and directly affects the amount of the crop. During the growing season, wheat needs around 130-200 kg of nitrogen per hectare under average weather conditions (Tajnšek, 1988).

The usual method of determining the application of nitrogen involves a field measurement with a chlorophyll meter, which determines the actual supply of plants with nitrogen in the leaves based on the content of chlorophyll in them. The proportion of nitrogen in plants is also checked in laboratories. While the stocking in the soil is mainly checked by analyzing individual soil samples. These methods provide reliable results, but are often more difficult to implement for practical and economic reasons. The surfaces are often extensive and individual areas are too specific and variable in terms of nitrogen content (Weber et al. 2017). Establishing the correct fertilization with nitrogen and a special level, the fertilization must be regulated and adapted to various factors, such as e.g. variety, expected yield quantity and quality, soil nitrogen availability, mineralization potential and plant needs during the growing season (Bavec and Bavec, 2014).

Modern agriculture emphasizes both environmental protection and the economic aspect of production. The correct determination of nitrogen requirements is crucial, as surpluses in fertilization can make production more expensive, and this also leads to leaching and evaporation of the fertilizer, which has a negative impact on the environment. Of course, we have to make sure that fertilization is sufficient in order to achieve the desired yield (Gastal and Lemaire, 2002).

MATERIAL AND METHODS

As part of the EIP Precision Agriculture and Digitization project, an experiment with precision fertilization on a winter wheat crop was carried out on the Štefan Cigut farm. The experiment was carried out on gerk no. 6413883, name: Velki travnik, surface area 11.73 ha. The area on which the experiment was carried out is very heterogeneous, because compaction was made in the previous year and now the new area consists of several smaller areas, which were cultivated by different farmers, and different crops were also grown. Aggregation or consolidation of agricultural land is an administrative procedure in which the land in a certain area is consolidated and redistributed among the previous owners so that everyone gets the most rounded land (Sklad, 2024).

In the experiment, the winter wheat variety RGT REFORM was sown on 23 October 2023. Pre-sowing tillage was done without plowing in a conservation way using a circular harrow and a Horsch Pronto planter. The machinery used in the experiment is presented in Table 1.

Table 1. The machinery used in the experiment

Basic tillage tractor	Fendt 724
Tractor for fertilizing, spraying,...	Fendt 516
Seeder for compact sowing	Horsch pronto
Mineral fertilizer spreader	Amazone ZA-TS 4200
Sprayer	Amazone UF2 2200
Combine harvester	New holland CR 9060

The experiment compared fertilization of winter wheat with a fixed dose of nitrogen over the entire area and a variable dose of nitrogen. The area with the wheat crop was divided into two parts. Half of the area was fertilized with a variable dose of fertilizer, and another part of the area with a fixed dose of KAN fertilizer. The KAN fertilizer dose on the surface where the fixed dose was always equal to the average fertilizer dose on the surface where the variable dose was applied. Both treatments were fertilized with the same average fertilizer doses. The wheat was fertilized with four doses of KAN fertilizer (Table 2). The preparation of fertilization maps was carried out in the GeoPard Agriculture program. Sampling folders (Nmin soil and plant tests) were prepared on the basis of satellite images. Samples were then taken from the assigned zones. They were analyzed for nitrogen content. Then folders for nitrogen fertilization were made, after which top dressing was carried out.

Table 2. Dates of fertilization and doses of nitrogen fertilizer

Fertilization stages	Fertilizer	Date	Amount of fertilizer
1.	KAN 27 %	17.2.2024	230 kg ha^{-1}
2.	KAN 27 %	19.3.2024	187 kg ha^{-1}
3.	KAN 27 %	19.4.2024	183 kg ha^{-1}
4.	KAN 27 %	12.5.2024	156 kg ha^{-1}

The harvest was done on 10.7.2024 with a New Holland CR 9060 combine, and a crop map was also made. The data was then processed in the Ag Leader program.

RESULTS AND DISCUSSION

The harvest of the experiment was carried out on 10.7.2024 with a New Holland CR 9060 combine with simultaneous crop mapping. Based on the yield map, the average yield was calculated, which was 6.749 t ha^{-1} on the surface with a fixed dose of N fertilizer (Figure 1), and the yield on the variant with variable fertilization was 6.716 t ha^{-1} (Figure 2).

Cultivar RGT REFORM for intensive technology requires higher doses of mineral nutrition, and is characterized by high grain productivity. Potential yield is 11-12 t ha^{-1}, the average yield on the farm is 9.4 t ha^{-1} (Agroprodservice, 2024). In our case, the yields are much lower, which confirms the poorer productive capacity of the soil for higher yields. The reason is the large heterogeneity of the surface, as a result of land compaction in the previous year.

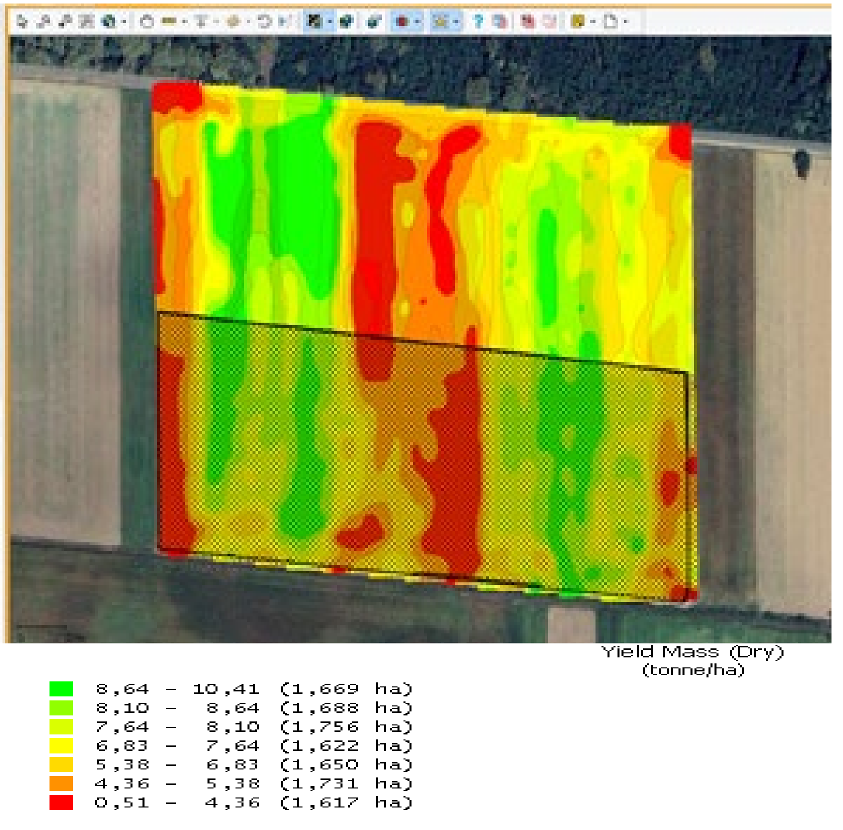

Figure 1. Yield map for the area where fixed doses of N fertilizers were applied over the entire area (circled part)

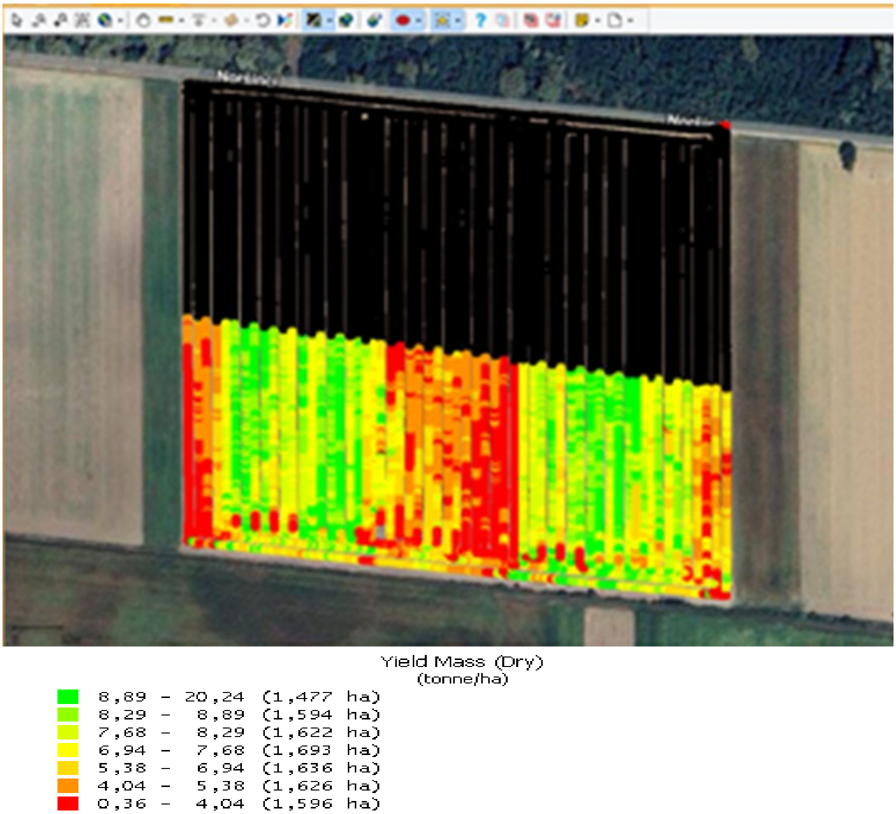

Figure 2. Yield map for the area where variable doses of N fertilizers were applied (colored black)

Yields in both variants of the study were practically the same (the difference is +33 kg/ha in the variant with a fixed dose), although we would expect that the yield of wheat in the variant with variable fertilization would be higher compared to the fixed dose of N over the entire area. The reason that this was not the case is the great heterogeneity of the surface, the cause of which is the implementation of compaction in the previous year. For this reason, it is estimated that the limiting factor for a higher yield was not a lack of nitrogen, but in individual parts of the surface, low pH of the soil, basic soil stocking with phosphorus and potassium, and high soil compaction in individual areas of the field. We also noticed all this during the growing season as poorer crop growth in certain areas of the field.

For this reason, it would be reasonable to repeat the experiment on the surface, where we would not have the previously mentioned limiting factors, such as soil compaction, low pH and basic nutrient supply. In this case, nitrogen will have a major impact on the quantity and quality of the crop.

CONCLUSIONS

Due to consolidation carried out in the previous year, the new and larger area consists of several smaller areas cultivated by different farmers. Various crops were grown. The main factor for a higher yield is not a lack of nitrogen, but different pH values of the soil, the basic supply of soil with phosphorus and potassium, and high soil compaction. During the growing season, we noticed poor growth of the crop in certain areas of the field. In our case, there are two solutions. The first involves a multi-year experiment where we could see differences over a longer period. Further research needs to be caried out, because no valid conclusions can be made based on one year. Another solution is that the experiment must be repeated on a surface where there would be no limiting factors, such as soil compaction, low pH, and basic nutrient supply. Nitrogen will play a major role in this case in the quantity and quality of the crop.

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EVALUATION OF NUTRITIONAL PARAMETERS OF WATERMELON *(CITRULLUS LANATUS)* SEEDS AS A POSSIBLE USE IN ANIMAL FEED FORMULATION

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ABSTRACT

Watermelon (Citrullus lanatus) is the fruit of a plant with the same name from the Cucurbitaceae family belonging to the genus Citrullus. This fruit has excellent nutritional properties and a rich phytochemical profile with numerous health benefits. It has a high content of antioxidants and contains various bioactive chemicals, such as carotenoids, phenolic compounds, vitamins, minerals, amino acids, and alkaloids, which are all distributed and concentrated differently in the pulp, peel, leaves, and seeds. Watermelon seeds, often considered a waste, are nutrient-rich, containing folic acid, protein, dietary fiber, minerals, fats, B-vitamin complex, and are also known for their remarkable antioxidant activity. This study investigated the nutritional composition of watermelon seeds commercialized in local agri-food markets for possible use as a feed fortifier. The results obtained from the analysis of nutritional parameters: 4.77 - 5.54% moisture, 2.71- 3.07% ash (minerals), 32.20 - 34.20% crude fat, 28.40 - 31.60% crude protein, 6.47 – 7,93% crude fibers, 18.80 - 24.10% carbohydrates, show that analyzed watermelon seeds contain significant amounts of crude fat, crude protein and minerals, sufficient amounts of crude fiber and carbohydrate and low amounts of moisture. Therefore, the nutritional composition of the analyzed watermelon seeds allows their inclusion as ingredients in animal feed formulation. Furthermore, utilizing this by-product from watermelon processing could constitute an ecological method for reducing environmental pollution.

Keywords: *watermelon seeds, nutritional properties, by-product*

INTRODUCTION

Watermelon (Citrullus lanatus), belonging to the tropical fruit family Cucurbitaceae, is one of the most cultivated fruits in the world (Yadav et al., 2022). As a fruit, watermelon is low in calories, salt, cholesterol and rich in nutrients, minerals, and phytochemicals (Yadav et al., 2022) with numerous health benefits such as improving cardiovascular health, hypotensive effect, lowering LDL (low-density lipoprotein) oxidation, combating age-related degenerative diseases and certain types of cancer (Meghwar et al., 2024).

The edible portion of the Citrullus lanatus fruit is eaten, while the other portion is discarded. Citrullus lanatus is rich in antioxidants and contains a variety of bioactive chemicals, such as carotenoids, phenolic compounds, vitamins, amino acids, and alkaloids, that are all distributed and localized differently in the pulp, peel, leaves, and seeds (Jibril et al., 2019).

Regarding the nutrition profile of watermelon, Nadeem et al. (2022) cite that one cup (152 g) of watermelon contains 11.6 g carbohydrate, 1.863 mg sucrose, 2.433 mg glucose, 5.174 mg fructose, 92.4 mg maltose. Watermelon has a protein content of 0.9 g per serving. Watermelon also contains β-carotene (0.467 mg), β-cryptoxanthin (0.12 mg/100g), lycopene (6.9 mg), vitamin C (0.0125 mg), betaine (0.5 mg), pantothenic acid (0.3 mg), choline (6.3 mg) and folic acid (0.0046 mg). Mono-unsaturated and polyunsaturated fatty acids are found in trace amounts of 0.1 g each, while the phytosterol content is 3.1 mg. Regarding minerals, noticeable found in watermelon are 10.8 mg Ca, 15.4 mg Mg, 16.9 mg P, 173 mg K, 1.5 mg Na, 0.2 mg Zn, 0.1 mg Cu, 0.0006 mg Se, and 0.0023 mg F. Only half of a watermelon fruit is consumed - i.e. the pulp, while the other half, consisting of the rind and seeds (about 40-45%), is generally discarded as solid waste (Capossio et al, 2022).

Watermelon seeds are known to be highly nutritious; they are rich sources of protein, B vitamins, minerals (such as Mg, K, P, P, Na, Fe, Zn, Mn, Cu), and fats, among others, as well as phytochemicals (Tabiri et al., 2016). According to Gabriel et al. (2018), watermelon seeds show the following proximate composition: 19.43% crude protein, 26.10% crude fiber, 21.54% crude lipid, 5.03% ash, 10.92% moisture, 16.68% carbohydrates. These nutritional values make using watermelon seeds to develop novel health-promoting functional foods possible. Opara et al. (2019) found that C. lanatus seeds have an increased content of nutritional components and 4.20% moisture, 30.30% crude lipid, 32.08% crude protein, 7.20% crude fiber, 2.70% ash, and 23.2% carbohydrates.

In addition, the analyzed seeds also contain significant amounts of phytochemicals, such as alkaloids, steroids, glycosides, saponins, flavonoids, terpenoids, and tannins. Kausar et al. (2020) showed that watermelon seed flour can prepare cookies with improved protein, fat, fiber, and ash content.

The proximate composition of watermelon seeds flour is as follows: 8.25% moisture, 3.73% ash, 46.78% crude fat, 26.37% crude protein, 4.10% crude fiber, and 10.77% carbohydrates (Kausar et al., 2020). The fact that watermelon seeds contain significant amounts of nutritional compounds was also noted by Jaroszewska et al. (2023), who reported that watermelon seed flours contain 20.50% crude protein, 25.20% total lipids, and essential mineral elements. Studying the utilization of proof watermelon seed in bread production, Wójcik et al. (2023) showed that flours obtained from watermelon seeds contain 20% protein, 9% fat, and 60% carbohydrates. The seeds of Citrullus lanatus, considered waste materials, are rich in therapeutic nutrients such as vitamins, minerals, fatty acids, phytosterols, proteins, phenolic compounds, dietary fiber, amino acids, and possess antioxidant activity contributing to increase immunity, aid digestion and maintaining the health of the nervous system and heart, Saeed et al. (2024) and Naveena et al. (2024).

Watermelon seeds may also contain antinutrient compounds such as tannins, phytates, or oxalates, which generally reduce the bioavailability of nutrients such as proteins, vitamins, and minerals (Kolawole Sunday et al., 2013). Several methods of reducing antinutrient content have been reported, including high-temperature soaking, fermentation, extrusion, roasting, blanching, and sprouting (Addo et al., 2018).

From the above, it can be observed that watermelon seeds contain significant amounts of nutritional compounds, especially proteins, fats, but also minerals, fibers, and carbohydrates, which vary within wide concentration limits, depending on several factors, including the melon variety from which they originate (soil, climate, post-harvest processing and storage conditions), seed collection, etc. (Nadeem et al., 2022).

To provide a clearer understanding of the nutritional composition of watermelon seeds, we present below the findings from previous studies, which outline the concentration ranges of key nutritional parameters.

Results obtained by different researchers show that watermelon seeds contain sufficient nutritional compounds (proteins, fats, minerals, carbohydrates, and fibers) to be included in feed formulations as sources of nutrients. On the other hand, the higher cost of some feed ingredients (soybean, peanut oilcake, maize, and sorghum) used in animal feed requires using unconventional materials such as watermelon seeds for feed formulation (Mudi et al., 2024). In order to conduct a nutritive evaluation of watermelon seeds (Citrallus lanatus), Mahala et al. (2010) found that watermelon seeds and seed cake contain 20.87% crude protein, 38.39% crude fiber, 30.13% ether extract and 4.23% ash and 96.1% dry matter, respectively 25.39% crude protein, 27.39% crude fiber, 7.84% ether extract, 2.7% ash and 95.6% dry matter. The authors of this study concluded that the watermelon seed cake is an excellent protein supplement. Acar et al. (2012) show that watermelon (Citrullus lanatus vercitroides) seeds contain significant amounts of nutritional compounds: 4.56% moisture, 3.98% crude protein, 52.34% crude oil, 3.73% crude ash, 5.99% crude fiber and recommend their use in animal feed.

In a study regarding the effects of feeding watermelon seed meal and full-fat seed on broiler chicks' growth, Shazali et al., 2013 determined the following proximate composition of watermelon full-fat seed (on dry matter basis): 97.3% dry matter, 17.7% crude protein, 22.8% crude fiber, and 4.3% ash. The study's authors recommended watermelon seeds as feed ingredients in broiler diets. According to Das & Mallikarjunarao (2016), watermelon seeds resulting as agro-industrial waste contain significant amounts of nutritional compounds: 4.3% moisture, 34.1% protein, 52.6% fat, 3.7% minerals, 0.8% fiber, and 4.5% carbohydrate. Therefore, this by-product from the processing units can be used in the industry as an ingredient in food or animal feed. Results obtained by Tabiri et al. (2016), when analyzing seeds from three watermelon varieties (Charleston gray, Crimson sweet, and Black diamond) indicated that watermelon seeds with moisture contents in the range of 7. 40 - 8.00% contain 26.50 - 27.83% fat, 16.33 - 17.75% protein, 39.09 - 43.28% fiber, 2.00 - 3.00% ash, 9.55 - 15.32% carbohydrate and an energy value of 354.05 - 369.11 kcal/100g. In addition, the analyzed seeds also contain essential amounts of minerals: 0.17-0.22% P, 0.11-0.16% Ca, 0.02-0.09% Mn, 3.40-3.85% K, 0.07 - 0.17% Na, 0.14 - 0.17% Mg. 2.72 - 4.60mg/100g Fe, 0.38-0.58 mg/100g Cu and 0.66 - 3.71mg/100g Zn. The study's authors suggest that watermelon seeds are a considerable source of nutrients in human and animal diets. Analyzing the nutrient composition of processed and unprocessed watermelon seeds for possible use in feed formulation, Milala et al. (2018) showed that they have the following proximate composition: 5.06% moisture, 2. 98% ash, 32.90% crude fat, 49.70% crude protein, 2.10% crude fiber, 6.06% crude carbohydrate - in unprocessed seed and 6.29% moisture, 2.59% ash, 2.59% ash, 47.1 % crude fat, 68.03% crude protein, 1.13% crude fiber, 24.99% crude carbohydrate - in processed seed. Results obtained by the authors of this study showed that the crude protein levels in processed and unprocessed watermelon seeds are high enough for their inclusion in feed formulation as a source of protein.

Furthermore, processed seeds' carbohydrates and fat content are higher than unprocessed seeds, making them a considerable energy source in animal feeds. The same study authors cite Pal and Mahdevan, who recommended the incorporation of that watermelon seed cake (with the content of digestible crude protein and total digestible nutrients found to be 20.42 and 52.73 kg/100kg respectively) in the feed of Kumaoni bullocks (Milala et al., 2018). Therefore, the crude protein, fat, carbohydrates and minerals, and vitamin A levels in watermelon seeds suggest their introduction in animal feed formulation. Information about the nutritional compounds and utilization of the watermelon waste were also reported by Galit et al., 2019, who cite the following nutritional values: 34.1- 35.66 % protein, 50 - 52.6% fat, 5.0% fiber, 100-150 mg/100g Ca, 16.8 - 937 mg/100g P, 1.2 - 10.6 mg/100g Zn, 11.4 mg/100g Mg, 7.8 mg/100g K, 5.7 mg/100g Na. The analyzed seeds' rich protein and fat content indicate they could be used in food formulations or animal feed (Galit et al., 2019). In evaluating the medicinal properties and possible nutrient composition of Citrullus lanatus (Watermelon) seeds, Enemor et al. (2019) found that watermelon seeds have a nutritional index and contain 48.68% moisture, 22.77% crude fat, 13.99% carbohydrate, 8.9% protein, 0.060 ash, and 2% fiber; in addition, the analyzed seeds were rich in phytochemicals, vitamins A and C (68.13, respectively 19.45 mg/kg) and mineral elements (such as K, Fe, Mg, Na). The study's authors prove that watermelon seeds can be a good source of vitamins and minerals in the human diet and animal feed. According to Mudi et al. (2024), the nutritional quality of watermelon seed meal is comparable to that of proteins from oilseeds, including soybeans. The authors of the study found that watermelon seed flour contains sufficient amounts of nutritional compounds: 6.26% moisture, 2.74% ash, 10.60% fats, 21.50% crude protein, 6.50% crude fiber, and 56.40% carbohydrate, to serve as an ingredient in fish feed. Saeed et al., 2024 investigated the nutritional and functional properties and antioxidant profile of Cucumis melo and Citrullus lanatus seeds. The results presented by the authors of this study showed that watermelon seeds contained important protein, fat fiber, and essential elements: 7.4% moisture, 2.1% ash, 15.6% crude protein, 27.4% crude fat, 7.8% crude fiber, respectively 86.6 mg/100 g Na, 236.7 mg/100 g K, Ca, 25.0 mg/100 Mg, 11.0 mg/100 Zn. The study's authors support using watermelon seeds as ingredients in the formulation of fortified food products and show that the recovery of watermelon seeds as food additives can contribute to reducing agro-industrial wastes.

From the above-presented data, the composition of watermelon seeds showed different percentages of moisture, ash, fat, protein, fiber, and carbohydrate contents. The possible reason for such difference could be attributed to differences in varieties, mode of cultivation, pedoclimatic conditions, etc (Tabiri et al., 2016).

This study aims to determine the nutritional composition of watermelon seeds marketed in local agri-food markets for possible use in improving the nutritional quality of animal feed.

MATERIALS AND METHODS

Materials

Watermelon fruits were purchased from a local agri-food market in Timisoara (Romania). Three sample groups of watermelon seeds (W.M.S.) were formed on the agricultural plots, according to the three agricultural areas of watermelon culture, and were denoted by P1, P2, and P3. Watermelon seeds were extracted manually from the fruit pulp, after which they were washed and sun-dried. The dried seeds were ground using a kitchen grinder and stored in plastic containers for further analysis. Five samples from each group of watermelon seeds were analyzed.

Methods

The determination of nutritional parameters: moisture, ash, crude protein, crude fats, crude fiber, and carbohydrate in the powders of the three groups of watermelon seeds was carried out according to methods validated and recommended by Velciov et al. (2021) and Milala et al. (2018). The moisture content was determined by drying in an oven at 105 °C until constant weight. The Kjeldahl method determined the crude protein content; crude proteins were calculated as N × 6.25. The ash content was calcined in an oven at 600 °C for 3 hours. The crude lipids (fats) were extracted with petroleum ether using a Soxhlet apparatus. The crude fiber was extracted with 1.25% NaOH, drying the residue for one hour at 105 °C and calcination at 600 °C. The carbohydrate content was calculated using the ratio [100 - (moisture + protein + fat + ash)].

Statistical analysis

All the data was statistically analyzed for variance (ANOVA) using R version 4.4.1 (R Core Team 2024). The comparisons for means were made using Duncan's Multiple Range Tests (D.M.R.T.). Duncan's Multiple Range Tests or Duncan's New Multiple Range Tests provide significant levels for the difference between any pair of means, regardless of whether a significant F resulted from an initial analysis of variance. The Shapiro-Wilk test was used to assess the normality of the data (Ghosh & Mitra, 2020).

RESULTS AND DISCUSSION

The results obtained by analyzing the nutritional parameters of W.M.S. taken in the experiment are presented in Table 1. As can be seen from Table 1, the analyzed W.M.S. contains significant amounts of crude fat, crude protein and minerals, sufficient amounts of crude fiber and carbohydrate, and low amounts of moisture ranging in limits between 4.77-5.54% moisture, 2.71-3.07% ash (minerals), 32.20 - 34.20% crude fat, 28.40 - 31.60% crude protein, 6.47 - 7.93% crude fibers, 18.80-24.10% carbohydrates. The concentration levels of the analyzed nutritional parameters are generally within the range of values reported in previous studies. Several factors justify the differences: the species of the plant, the soil conditions, the climate and other factors of an anthropical or geogenic nature, the period of harvesting the leaves, and last but not least, the method of preparation and sample analysis (Velciov et al., 2023).

Table 1. The nutritional properties of watermelon seeds*

Specification	Nutritional values (%)					
	Moisture	Ash	Crude fat	Crude protein	Crude fibers	Carbohydrates
Plot 1 (P1)	4.77±0.24a	3.07±0.37a	32.20±0.78a	28.40±0.81a	6.67±0.3a	24.10±0.44a
Plot 2 (P2)	5.54±0.18b	2.71±0.20a	33.20±0.83ab	31.60±0.94b	7.93±0.37b	18.80±0.75b
Plot 3 (P3)	5.12±0.39ab	2.88±0.15a	34.20±0.82b	29.50±0.69ab	6.47±0.40a	21.50±0.66ab
Mean value	*5.14±0.31*	*2.87±0.13*	*33.20±0.82*	*29.83±1.33*	*6.99±0.60*	*21.47±2.18*

*All data were expressed as means ± standard error of five replicates; mean scores with different letters on the same column are significantly different (P0.05).

The moisture content of any food material is a measure of the shelf life of food, and it indicates how long a food material can be kept without spoilage (Milala et al., 2018). Moisture content is essential for food preservation and, hence, in food processing (Velciov et al., 2022).

The analyzed W.M.S. samples contain relatively low amounts of moisture, within the 4.77 - 5.54% range. The highest moisture value (5.54%) was determined in P2, which was statistically significantly higher than the values determined in P1 (4.77%) and P3 (5.12). No statistically significant differences exist between the moisture determined in P1 and P3. The mean value of moisture (5.14%) indicates that the analyzed dried watermelon seed powder does not present a significant risk of degradation over time.

The ash content of the samples indicates the content of inorganic matter (Tabiri et al., 2016), i.e., the sum of the mineral elements that are part of the analyzed samples (Velciov et al., 2022). The mineral content of the analyzed W.M.S. seeds was determined in very close concentrations within the range of 2.71 - 3.07%. No statistically significant differences are reported between the values determined in P1 (3.07%), P2 (271%.) and P3 (2.88%). The mean value of ash content (2.87%) reveals that the analyzed watermelon seeds contain significant amounts of essential mineral elements that provide a wide range of health benefits for the body's normal functioning (Mehra et al., 2015).

Lipids are essential macronutrients that play important physiological and biochemical roles in the functioning of the human body, such as energy storage, structural components of biological membranes, electron carriers, enzyme cofactors, light-absorbing pigments, hydrophobic anchors for proteins, and emulsifying agents in the digestive tract (Velciov et al., 2022). Fats are also excellent energy sources, improving the transportation of fat-soluble vitamins (Velciov et al., 2022).

The fat concentration in analyzed W.M.S. samples range from 32.20 - 34.20%. Duncan's test shows statistically significant differences between the fats determined in P1(32.20%) and P3 (34.20%). No statistically significant differences were reported between the fats determined in P2 (33.20%) and P3. The mean value of the fat concentration (33.20%) shows that the analyzed W.M.S. contains increased amounts of fats, indicating that they represent an essential source of calories.

Proteins are essential nutrients for the body (Mehra et al., 2015). Proteins are important biomolecules for body homeostasis (Mehra et al., 2015). Protein deficiency is closely related to several diseases caused by energy deficiency: mental disorders, failure of various organs, edema, and weakened immune system (Velciov et al., 2022). Protein and energy are considered essential components of forages (Mahala et al., 2010).

The protein concentration in the analyzed W.M.S. samples ranged from 28.40 - 31.60%. Comparing the crude protein content values among the three plots, there are statistically significant differences between P1 (28.40%) and P2 (31.60%). No statistically significant differences were determined between P2 and P3 (29.50%). The mean value of this nutritional parameter (29.83%) shows that W.M.S. is rich in protein, which can be used in feed formulation as a source of protein.

The interest in the knowledge of dietary fiber content is closely associated with its role in water absorption and intestinal tract regulation, cholesterol reduction, and glucose regulation (Velciov et al., 2022). The crude fiber in the diet consists mainly of plant polysaccharides that cannot be digested by human dietary enzymes, such as cellulose, hemicelluloses, and some materials that make up the cell wall (Opara et al., 2018). This suggests that watermelon seeds would provide additional dietary fiber. The crude fiber of any seed indicates the presence of a reasonable quantity of trapped water (bond) held by the hydrophilic polysaccharides of the fiber (Milala et al., 2018). The lower crude fiber value suggests an advantage to monogastric animals, which are known to have little ability to digest fibrous materials (Amadi et al., 2018).

The concentration of crude fibers in W.M.S. samples show relatively close values ranging from 6.47 to 7.93%. However, the highest fiber content was determined in P2 (7.93%). Statistically significant differences were identified between the fiber content of P2 (7.93%), P1(6.67%), and P3 (6.67%), respectively; there are no statistically significant differences between the fiber content between P1 and P3. These values are close to the value obtained by Opana et al., 2018 when determining under similar conditions crude fiber (7.20%) from Citrullus lanatus seed. The mean value of crude fiber content (6.99%) shows that the analyzed W.M.S. exhibits relatively low crude carbohydrate contents but sufficient to be incorporated in the feed.

Carbohydrates are the immediate energy source for the body in the form of calories, which play an essential role in the normal functioning of body cells, tissues, and organs (Saeed et al., 2024). These help in fat utilization, protecting cells against external harmful effects (Velciov et al., 2022). According to Williams and Lenkat (2018), carbohydrates play an important role in the diet as energy reserves, e.g., glucose, can be converted into many natural substances such as fats, proteins, and vitamins (Williams et al., 2018). Although there are different types of carbohydrates, only total carbohydrates are considered in food and remain when protein, fat, moisture, and ash of food have been removed (Velciov et al., 2022). The carbohydrates and fats contents of W.M.S.s make it a considerable energy source in animal feeds [Milala et al., 2018]. W.M.S. samples contain appreciable amounts of carbohydrates, their concentration ranging from 18.80 - 24.10%. These values are close to the value obtained by Opana et al., 2018 when determining under similar conditions carbohydrate (23.52%) from Citrullus lanatus seed. The analyzed seeds from P1(24.10%) are more prosperous in carbohydrates. There are statistically significant differences between the carbohydrate content of P1 and P2 (18.80%). No statistically significant carbohydrate differences are reported in P2 and P3(21.50%). The average carbohydrate concentration (21.47%) reveals that the analyzed W.M.S. contains sufficient carbohydrates that can be converted into fat, protein, and vitamins. It can be shown that watermelon seeds contain a total of 21.5% carbohydrates, of which 6.7% are fibers, and the rest consists of other forms of carbohydrates, such as sugars and possibly starch. Finally, it can be stated that the watermelon seeds taken in the experiment contain sufficient amounts of nutritional compounds to be used for feed improvement.

CONCLUSIONS

Watermelon seeds, a by-product of watermelon processing, still contain sufficient nutrients and phytochemicals. The results obtained from the analysis of the nutritional parameters of watermelon seeds (mean values): 5.14% moisture, 2.89% ash, 33.22% fat, 29.84% protein, 6.69% crude fiber, and 21.49% indicate that they contain significant amounts of protein, minerals, and adequate carbohydrates and fiber to be used for improving the nutritional quality of animal feed.

Moreover, the high content of phytochemicals in watermelon seeds promotes their use in animal feeding. On the other hand, the higher cost of some ingredients used in formulating animal feed (soy, peanut meal, corn, and sorghum) necessitates the introduction of unconventional materials, such as watermelon seeds, into the diet.

Additionally, using watermelon seeds as a by-product could constitute an ecological approach to reducing waste from watermelon processing.

We consider it important to conduct studies on the nutritional content and the relationship between fiber and carbohydrate levels; these will be the subject of future research.

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50. ACTUAL TASKS ON AGRICULTURAL ENGINEERING

Preliminary communication

THE INFLUENCE OF THE CHEMICAL COMPOSITION ON THE PHYSICAL QUALITY OF PELLETED FEED

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ABSTRACT

Pelleted feed is an important part of modern animal nutrition and offers advantages such as better nutrient distribution, higher feed intake and lower losses. However, the physical quality of the pellets is critical to maintaining these benefits, as poor quality pellets tend to degrade, resulting in nutrient losses and lower animal productivity. The durability and strength of the pellets depends on the composition of the feed and the processing conditions. The most important factors include starch gelatinisation, protein denaturation, fibre content, fat content and moisture balance. In this study, the relationship between the chemical composition of pelleted feeds and their physical properties, in particular pellet durability index (PDI) and breakage strength (BS), is investigated. Thirteen different feed mixtures for different animal species were analysed, their nutrient content and the durability of the pellets were evaluated. The results show that a higher starch and protein content increases the durability of the pellets, while a too high fibre and fat content can weaken the pellet structure. Statistical analysis confirmed a significant correlation between protein content and pellet durability, while fibre content has a complex interaction with pellet strength. Understanding these interactions allows producers to optimise formulations, improve feed efficiency, reduce waste and ensure consistent animal performance. The use of additives such as lignosulphonates or plant-based adhesives is recommended to increase the durability of fibre-rich pellets. Regular monitoring and *adjustment of feed composition is essential to maintain optimum pellet quality in animal feeding.*

Keywords: *pellets, feed, chemical composition, pellet durability index, breaking strength*

INTRODUCTION

Pelleted feed is an essential part of modern livestock nutrition and offers numerous benefits that help improve animal performance and operational efficiency. Key benefits include even distribution of nutrients, improved feed intake and minimization of feed wastage. Despite these benefits, the physical quality of the pellets remains a critical factor in realizing their full potential. Poor quality pellets tend to degrade during handling, transportation and feeding, which can lead to nutrient losses, increased feed wastage and reduced animal performance. To ensure high quality pellets, both the chemical composition of the feed and the processing conditions must be carefully considered, as these factors have a direct impact on key metrics such as Pellet Durability Index (PDI) and breaking strength. These metrics measure the structural integrity and hardness of pellets, both of which are critical to maintaining feed quality throughout the supply chain and ensuring optimal animal performance (Briggs et al., 1999; Samuelsen et al., 2021).

The chemical composition of feed plays a decisive role in determining the physical quality of pellets. Starch is one of the most important components in this respect. During the pelleting process, starch undergoes a physical transformation known as gelatinization. This occurs under the influence of heat and moisture, causing the starch granules to swell and gelatinize. Gelatinized starch acts as a natural adhesive, binding feed particles together and significantly improves the structural integrity of the pellets. Ingredients such as maize, wheat and sorghum, which are rich in starch and have a high gelatinization potential, are particularly advantageous for pellet production (Thomas et al., 1998). The extent of gelatinization depends on several factors, including the moisture content of the feed mash, the conditioning temperature and the residence time in the conditioner of the pellet mill. A moisture ledvel of 15% to 18% and temperatures between 70°C and 90°C are usually required to achieve optimum gelatinization. Insufficient gelatinization, which is often due to insufficient moisture or heat, results in weak pellets that crumble easily during handling and thus impair feed quality and efficiency.

Proteins also play a decisive role in the formation and durability of pellets. During the pelleting process, proteins are denatured by the application of heat and mechanical energy, which changes their structure and improves their adhesive properties. This denaturation process facilitates the binding of the feed particles and contributes to the formation of a strong and cohesive pellet matrix. Protein-rich ingredients such as soybean meal, rapeseed meal and fish meal are particularly effective in enhancing pellet durability (Wood, 1987). However, the effects of proteins on pellet quality depend on their source and processing conditions. Excessive heat during processing can lead to degradation of proteins, which reduces their binding capacity and negatively affects pellet durability. In addition, proteins interacting with other components, such as starch, affect the overall cohesion and integrity of the feed matrix, highlighting the complex interplay of feed components in determining pellet quality (Kaliyan and Morey, 2009).

The fiber content of the feed presents a more differentiated challenge for pellet quality. Insoluble fibers, such as those found in wheat bran or rice hulls, tend to reduce the durability of the pellets as they weaken the binding capacity of the feed matrix. In contrast, moderate amounts of soluble fibers can improve the pellet structure by increasing the cohesion between the particles. To achieve optimal pellet quality, it is important to find the right balance of fiber. Too high a fiber content not only affects the structural strength of the pellets, but also increases the abrasiveness of the feed, which leads to wear on the pelleting line components. To overcome these challenges, feed formulations with high fiber content often require additional binders or adjustments to processing parameters, such as higher compaction ratios or longer conditioning times, to obtain acceptable pellet quality (Astuti et al., 2022; Kaliyan and Morey, 2009).

Fats and oils play a dual role in the pelletizing process. On the one hand, they act as lubricants, reduce friction in the die and improve throughput, while reducing energy requirements. On the other hand, they have a negative effect on the durability of the pellets, as they reduce the cohesion of the particles. High-fat feeds are particularly prone to producing weak pellets, so the use of binders or other strategies is necessary to ensure adequate durability (Abdollahi et al., 2013).

Moisture content is also critical to the pelletizing process. Adequate moisture content facilitates particle binding by softening the feed ingredients and allowing gelatinization of the starch. However, both too low and too high a moisture content can have a negative effect on pellet quality. A low moisture content results in brittle pellets, while a high moisture content can cause the pellets to disintegrate during storage and handling. Maintaining an optimal moisture content is crucial for consistent pellet durability and quality (Corzo et al., 2011).

Additives are often used to improve the physical quality of pellets. Binders such as lignosulfonates, bentonite and guar gum are particularly effective in improving the cohesion of the pellets. These substances fill the voids between the particles and strengthen the feed matrix, resulting in stronger and more durable pellets. Other additives, such as emulsifiers and enzymes, change the physical properties of the feed components and thus improve their pelletability. Conditioning agents such as molasses and whey are also used to improve the moisture retention capacity of the feed, which enables better heat transfer during conditioning and contributes to a better durability of the pellets (Behnke, 1996).

The Pellet Durability Index (PDI) is a widely used indicator for assessing the physical quality of pellets. It measures the proportion of intact pellets remaining after mechanical stress, such as tumbling or shaking, and simulates the conditions during handling and transportation. The composition of the feed, especially the content of starch, protein and added binders, has a direct influence on the PDI. A high PDI indicates strong, durable pellets that are resistant to breakage, while a low PDI indicates pellets that are prone to crumbling, which can lead to increased fines and reduced feed efficiency. Ingredients rich in gelatinizing starch or denaturing proteins generally result in pellets with a higher PDI, as these components improve interparticle bonding and structural integrity (Thomas et al., 1998).

Breaking strength (BS), another important parameter for assessing pellet quality, refers to the force required to crush a single pellet. This measure of pellet hardness is influenced by the chemical composition, particle size and processing conditions. A high starch and protein content contributes to a higher crushing strength by improving the binding properties during pelletizing. Conversely, a high insoluble fiber or fat content can weaken the structural matrix and reduce pellet hardness. The breaking strength of pellets is particularly important for different livestock species as their feeding preferences vary. Poultry, for example, generally require harder pellets to minimize fines, while pigs prefer softer pellets to make them easier to consume (Muramatsu et al., 2015).

The interaction between the chemical composition of the feed and the processing parameters, such as temperature, pressure and conditioning time, plays an important role in determining pellet quality. For example, starchy feeds require sufficient moisture and heat to achieve optimal gelatinization, while high-fat feeds may require lower conditioning temperatures to prevent pellet breakdown. Matching processing conditions to the specific characteristics of the feed ensures consistent PDI and breaking strength, resulting in improved pellet quality and durability (Suwignyo et al., 2022; Xing et al., 2023).

High quality pellets with a high PDI and adequate BS are important to reduce feed wastage, improve feed intake and ensure consistent nutrient intake. Conversely, poor quality pellets that generate fines can reduce feed efficiency, lead to selective feeding behavior in animals and ultimately reduce production performance. Producing durable and stable pellets is critical to optimizing feed conversion and achieving economic efficiency in livestock production.

MATERIALS AND METHODS

Materials

To investigate the influence of chemical composition on the physical properties of pelleted feed mixtures (FM), randomly received at the Laboratory of the Department of Animal Nutrition, Faculty of Agriculture, 13 different feed mixtures were sampled in five replicates. Feed mixtures for different species and categories of animals were sampled; supplementary feed mixture (SFM) for horses under stress, SFM for sport horses, SFM for horses without oats, standard SFM for horses, SFM for horses without cereals, complete feed mixture (CFM) for carp, CFM starter for piglets, CFM for growing piglets, SFM for goats, CFM for growing broilers, CFM for turkeys, CFM for laying hens and CFM for rabbits.

Methods

The determination of nutritional parameters of the pelleted feed mixtures was carried out in the laboratory of the Department of Animal Nutrition of the Faculty of Agriculture. The following reference methods were used to analyse the content of individual feed components: for crude protein HRN ISO 5983-2: 2005, for crude fibre HRN ISO 6865: 2001, for crude ash HRN ISO 5984: 2004 (ISO 5984.2002), for crude fat HRN ISO 6492: 2001, and for moisture HRN ISO 6496: 2001. The mineral composition of the samples was determined for calcium according to the complexometric method RU-5.4.2-11, 1st edition, for phosphorus spectrophotometrically HRN ISO 6491:2001 and for sodium according to the method of flame emission spectrometry HRN ISO 7485:2001.

Pellet durability refers to the ability of the pellets to withstand abrasion during storage and transport. In practise, pelleted feed mixtures are susceptible to damage during handling if the pellet rubs against a surface or hits an object during movement. The durability of pellets is expressed by the Pellet Durability Index (PDI), which is determined according to the method of Pfost (1976). 500 grammes of sieved pellets were placed in a 30 cm x 12 cm metal box containing a 23 cm long and 5 cm wide partition centred diagonally in the box. This box was rotated at 50 revolutions per minute for 10 minutes. The pellets were then removed and sieved again. The Pellet Durability Index (PDI) is defined as the percentage of pellets that survived the test and remained on the sieve.

A commonly used technique for the measurement of material strength is the compression of a sample between two plates. To measure the forces required to brake a pellet, a universal testing machine was used to compress the pellet (Figure 1). The pellet sample was placed on the fixed plate and pressed with a moving plate connected to the load cell until the pellet broke. The forces were measured by the data acquisition system, which included a dynamometer HBM S9M/1kN (Hottinger Baldwin Messtechnik, Darmstadt, Germany), amplifier HBM Quantum MX840B, and a personal computer. Series of 20 pellets from every feed mixture were tested to determine pellet breakage strength.

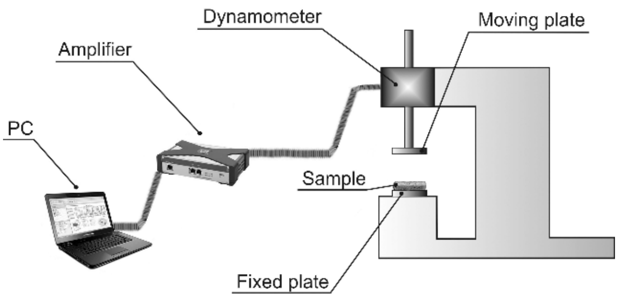


Figure 1. Schematic presentation of universal testing machine used to measure the breakage strength

Statistical analysis of the results obtained was performed using SAS statistical software (version 9.4; SAS Institute Inc., Cary, NC, USA). The chemical composition of the samples was determined in five replicates for each sample, while the physical properties of the pellets were determined in ten replicates. The mean values and other descriptive statistics parameters were determined using the LSMEANS command. In addition, the relationship between. The properties were analysed using the CORR procedure. The threshold for statistical significance was defined as $P < 0.05$.

RESULTS AND DISCUSSION

As expected, the chemical composition of the analysed feed mixtures was very different (Table 1). The expected differences arose because we had different pelleted feed mixtures in the study, i.e. feed mixtures for different species and categories of feed mixtures. For example, some of them are rich in ash (minerals), such as feed mixtures for non-calving animals, while others, such as feed mixtures for older animals, are poorer in minerals. In addition to the mineral and ash content, there are also significant differences in the crude protein percentage, which ranges from 12 to 24%, and especially in the fibre content, which ranges from 4 to 20% in pelleted feed mixtures, such as pelleted feed mixtures for horses without grain.

The ash content of animal pellets has a significant effect on their strength, with a higher ash content generally leading to weaker bonding between the particles and greater friability. Ash, which consists mainly of inorganic minerals such as silicon, calcium and phosphorus, does not contribute to the cohesive properties of the feedstock during pressing, unlike organic components such as proteins and starch (Thomas et al., 1998). Increased ash content can also affect moisture absorption, which is critical for optimal pellet formation, while feedstocks such as wheat bran, which naturally have a higher ash content, can reduce product quality and durability (Wood, 2011). In addition, ash content above the optimum level reduces the nutritional value of pellets, while pellets that are too brittle increase brittleness during transport, leading to economic losses (Briggs et al., 1999). In our study, the ash content ranged from 5% in goat feed mixtures to 14% in layer feed, as expected. However, no correlation was found with the ash content in the tested feed mixtures. However, a statistically significant correlation (p=0.009) was found for the content of the mineral sodium. In addition to the significant influence of sodium on the correlation of the PDI, a relatively high positive correlation of Na on the PDI of almost 70% was also found. (Figure 2).

Table 1. The nutritional and physical properties of peleted animal feed

Feed	**Chemical composition [%]**								**Physical properties**	
	Ash	CP	CF	Sta	EE	Ca	P	Na	BS [N]	PDI [%]
Horses-1	7.00	10.50	11.60	54.95	3.95	0.90	0.48	0.37	382.6	95.20
Horses-2	6.00	13.50	11.50	53.00	4.00	1.00	0.60	0.35	321.3	96.43
Horses-3	7.00	12.00	6.00	60.00	3.00	1.30	0.65	0.25	253.6	93.80
Horses-4	7.00	12.00	10.50	55.60	2.90	1.20	0.60	0.23	251.8	89.37
Horses-5	9.50	12.00	20.00	41.50	5.00	1.50	0.50	0.20	255.8	90.80
Fish	6.00	20.00	5.00	53.50	3.50	0.65	0.65	0.01	249.0	97.77
Pigs-1	6.50	20.00	4.50	53.50	3.50	0.85	0.60	0.20	217.9	96.47
Pigs-2	6.00	18.00	4.00	57.00	3.00	0.85	0.60	0.18	192.0	96.13
Goats	5.00	16.00	4.50	59.50	3.00	0.55	0.60	0.20	192.3	96.17
Broilers	6.00	18.00	4.00	56.00	4.00	1.00	0.50	0.10	146.2	96.20
Poultry	8.00	24.00	5.50	48.00	2.50	1.25	0.60	0.10	210.6	97.07
Layers	14.00	15.00	3.00	52.00	4.00	4.00	0.36	0.15	191.9	96.43
Rabbits	8.50	16.00	15.00	45.00	3.50	0.95	0.80	0.20	313.5	97.87
Descriptive statistics of parameters										
MEAN	7.42	15.92	8.09	53.04	3.53	1.23	0.58	0.20	244.5	95.36
SEM	0.64	1.10	1.44	1.50	0.18	0.24	0.03	0.03	17.9	0.72
SD	2.32	3.97	5.21	5.40	0.67	0.87	0.11	0.10	64.4	2.58
Minimum	5.00	10.50	3.00	41.50	2.50	0.55	0.36	0.01	146.2	89.37
Maximum	14.00	24.00	20.00	60.00	5.00	4.00	0.80	0.37	382.6	97.87

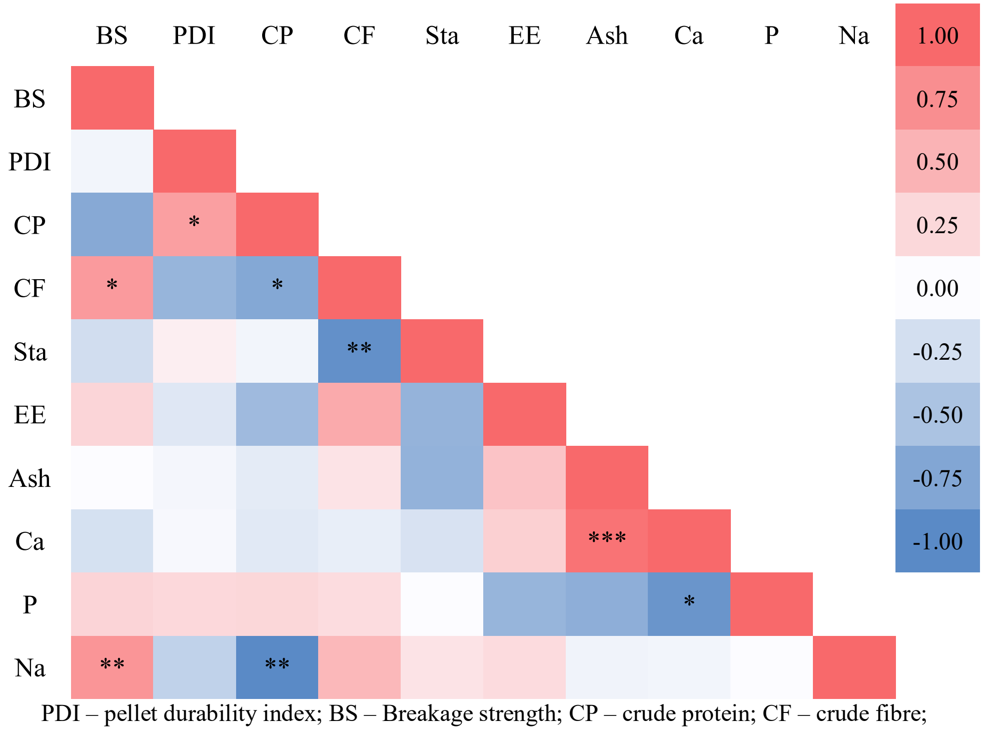
CP – crude protein; CF – crude fibre; Sta – starch; EE - extract ether; Ca – calcium; P – phosphorus; Na – sodium; BS – breakage strength [N]; PDI – pellet durability index; SEM – pooled standard error of the mean; SD – standard deviation.

The proportion of fat or vegetable oil in pelleted feed mixtures was between 2.5 and 5 % in horse feed mixtures, with the average oil content in pelleted feed mixtures being 3.5% (Table 1). This relatively low oil content had no effect on the physical properties of the pelleted feed, which is consistent with the studies of Brigges et al. (1999). In that study, the oil content of the rations varied between 2.9 and 7.5%, and the protein content was between 20.3 and 21.0%. The average PDI of all rations hardly changed and was between 84.0 and 88.8, but the durability of the pellets decreased significantly when the oil content reached 7.5%. Meal 1 had an oil content of 6.2% due to the soybean oil added to the ration, resulting in an average PDI of 57.2. The low PDI for meal 1 is due to the combination of low protein and high oil content. Based on the results of this study, the quality of the pellets is not affected when the oil content is below 5.6% and the protein content is 20%. Richardson and Day (1976) investigated the effects of adding animal fat to broiler diets consisting mainly of maize and soya beans and originally containing 2.9% fat. After the addition of fat to the preconditioning rations, the fat content ranged from 3.9 to 7.9%, with the corresponding PDI ranging from 82.0 to 49.2. When the total fat content exceeded 4.9%, the pellets were of poor quality.

In studies by Stevens (1987) and Winowiski (1998), the durability of pellets from feeds containing maize was compared with those in which the maize was partially or completely replaced by wheat. In both cases, the durability of the pellets was higher for pelleted feed containing wheat. This could be due to the higher crude protein content of wheat (13%) compared to maize (9%). Higher protein content increased pellet durability, with protein levels in the treatments being 16.3 and 21%, corresponding to an average pellet durability of 75.8 and 88.8, respectively (Briggs et al. 1999). Similar results were observed by Winowiski (1988) and Stevens (1987). Our pelleted feeds contained three levels of proteins. They can therefore be divided into those with 10.5 to 15% CP, an average CP content of 15-18% and protein-rich feed mixtures with 20-24% protein (Table 1). With regard to the protein content, a statistically significant, medium-strong correlation of the CP content with the PDI (p=0.02) and an almost statistically significant (p=0.055) correlation of the protein with the pellet strength value (BS) were found in agreement with the above-mentioned studies.

Wood (1987) investigated the functional role of starch and protein in the pelleting process. The addition of raw soybean flakes increased pellet quality compared to heat-treated denatured soybean meal. In addition, pregelatinised starch improved pellet quality compared to native starch. Woods (1988) concluded that protein has a greater effect on pellet quality than starch. This finding was recently confirmed by Briggs et al. (1999). In our study, the starch content ranged from 41.5 to 60 %, and the same pattern was also found, as no statistically significant correlation was found between starch and durability of pelleted feeds with starch content, but only with crude protein content.

Dietary fibres have a significant impact on the quality of animal pellets, as their presence influences the strength, cohesion and digestibility of the pellets. Crude fibres contained in ingredients such as wheat bran, alfalfa and soybean meal often affect pellet quality as they are stiff and cannot be compacted during pressing (Thomas et al., 1998). High fibre content makes it difficult to form strong bonds between the particles, resulting in more fragile pellets that break easily during transport and storage (Briggs et al., 1999). However, moderate amounts of fibre can contribute to structural stability and prevent excessive density of pellets, making them easier for animals to consume (Wood, 1987). In addition, fibre types also play an important role. Soluble fibres can improve the texture and cohesion of the pellets, while insoluble fibres such as cellulose increase abrasion resistance in the pelletiser, which can affect equipment wear and the consistency of the final product. A balanced ratio of fibre content in the formulation is important to ensure high quality pellets that meet technical and nutritional requirements.



PDI – pellet durability index; BS – Breakage strength; CP – crude protein; CF – crude fibre; Sta – starch; EE - extract ether; Ca – calcium; P – phosphorus; Na – sodium; probability of differences (p), *p ≤ 0.05; **p =≤ 0.01; ***P ≤ 0.001.

Figure 2. Correlation between nutritional and physical properties of pelleted animal feed

Dietary fibres have a significant impact on the quality of animal pellets, as their presence influences the strength, cohesion and digestibility of the pellets. Crude fibres contained in ingredients such as wheat bran, alfalfa and soybean meal often affect pellet quality as they are stiff and cannot be compacted during pressing (Thomas et al., 1998). A high fibre content makes it difficult to form strong bonds between the particles, resulting in brittle pellets that break easily during transport and storage (Briggs et al., 1999). However, moderate amounts of fibre can contribute to structural stability and prevent excessive density of the pellets, making them easier for the animals to consume (Wood, 2011). In addition, fibre types also play an important role. Soluble fibres can improve the texture and cohesion of the pellets, while insoluble fibres such as cellulose increase abrasion resistance in the pelletiser, which can affect equipment wear and the consistency of the final product. A balanced ratio of fibre content in the formulation is crucial to obtain high quality pellets that meet technical and nutritional requirements. In the present study, the fibre content, like all other substances, was highly variable, ranging from 3 % in layer pellets to 20 % in foal pellets (Table 1). We are aware that this high fibre content in horse and rabbit pellets affects the quality of the pellets and presents a particular challenge in their production, but with such high fibre pellets, their production would not be possible without the addition of some technical aids. Apart from these extreme CF contents in feed mixtures for rabbits and horses, the CF content very rarely exceeds 6%. In our study, no negative effect of CF on the physical properties of the pellets was found, but quite the opposite. A statistically significant correlation (r=0.65) was found between the BS and CF parameters, which is in contrast to the research of Buchanan and Moritz (2009), who found that a fibre content of 4 and even 2% had a negative effect on the quality of the pellets. However, the aforementioned problem is solved technologically by adding certain additives, such as plant adhesives obtained by extraction (Locust bean gum or Guar gum), as is the case in the production of pelleted feed mixtures in our research.

CONCLUSIONS

The physical quality of pelleted animal feed is decisively influenced by its chemical composition. Key components such as starch, protein, fibre and fat content determine the structural integrity of the pellet, while physical properties such as Pellet Durability Index (PDI) and Breaking Strength (BS) provide measurable indicators of quality. By understanding the interaction between feed composition and processing conditions, producers can optimise their formulations and produce high quality pellets that increase feed efficiency, reduce waste and improve animal performance. To meet the quality requirements of pellets with increased fibre content, additives are routinely used to maintain the desired strength and durability of the pellets. Therefore, regular monitoring of raw material composition and adjustment of pellet formulation is crucial to achieve optimal strength and quality of pellets for animals.

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ORCHARD SPRAYER PERFORMANCE: A METHODOLOGICAL APPROACH TOWARD ENVIRONMENTAL IMPROVEMENT

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ABSTRACT

Careful administering of plant protection products is key to reducing their environmental impact. This is especially important in orchards due to the way treatments are conducted. Appropriate treatments yield more and better food, entail economic savings for the farmers, safeguarded health of environment and general population.

The adoption and evaluation of appropriate technologies is key to improving treatments; new solutions of growing complexity are in growing demand. Reliable means to objectively compare machine performance are therefore required.

This work introduces the vision of the "technological chain". At one end of the chain is the characterisation of single components, such as nozzles and air distribution systems; the "functional performance" regards the interaction between the components, characterising the accuracy of distribution and efficacy of treatments; and the "environmental performance" concern the ability of the machine of limiting off-target losses, especially drift.

Fast, reliable measurements are necessary along the whole technological chain, from design to end users: they are essential for the maintenance and adjustment of sprayers in use and for the development and certification of new solutions.

This work recounts some experiences in evaluating components and whole sprayers, prospecting how to conceptually connect each link of the chain, with *beneficial implications on end-users, research & development, manufacture and decision-making.*

Keywords: *Plant protection, Orchard sprayers, Sprayer performance, Testing, Certification*

INTRODUCTION

Plant protection treatments pose serious risks to the health of operators, bystanders, and ecosystems (Butler Ellis et al., 2018): careful administering of these substances is key to reducing off-target environmental dispersions. This is especially important in orchards due to the way treatments are conducted (Cunha et al., 2012; Garcerá et al., 2017). The benefits of appropriate treatments are evident and widespread: better yields and food quality, economic savings for the farmers, safeguarded health of environment and general population. The adoption and evaluation of appropriate technologies, tailored to the specific context, is key to improving treatments; this awareness is rising among all stakeholders, from machine manufacturers to end users and consumers. Consequently, new solutions of growing complexity are in growing demand, and their performance will need to be reliably and objectively compared.

The most common method to compare different machines or configurations remains field testing, but has limited reliability (Gil et al., 2018) due to the high influence of numerous uncontrollable variables (to name a few, the weather, the plant training system, and its vegetative stage) (Donkersley & Nuyttens, 2011).

In light of the number of parameters affecting the quality of treatment and drift generation (Arvidsson et al., 2011), a more systemic approach, separating the various aspects of machine performance, allows to limit and control the different affecting factors. This can be done by breaking the problem up according to different levels of detail, building a sort of "technological chain". At one end of this conceptual chain is the performance of *single components* of the machine: the behaviour of each individual component is the starting point to the behaviour of the whole machine.

The second link concerns the functional performance of the machine, and takes into account the interaction between the single components. The *functional performance* contains all those aspects which affect the efficacy of the treatment: for example, the ability to uniformly distribute the liquid on the plant canopy, or to adapt the dosage (L ha^{-1}) as the advancement speed changes.

Finally, a third link can concern the interaction of the machine with the surrounding environment, analysing the *environmental performance*: chiefly, limitation of off-target losses, and reduction of drift.

Fast and reliable performance measurements are essential in all domains of interest (Mazzetto et al., 2020), from the design, manufacture and certification of new, appropriate solutions, to maintenance and adjustment of sprayers in use: all stakeholders can benefit from this systemic approach.

This work recounts the recent experiences at the Agroforestry Innovation Laboratory (AFI-lab) of the Free University of Bozen-Bolzano in evaluating orchard sprayers, components, and test methodologies themselves. Apart from the evaluation of single components and of functional performance of whole sprayers, research is ongoing into advanced sensing solutions for rapid characterisation of spray deposition and aerosol drift (Ali et al., 2024), leveraging a wind tunnel facility (Becce et al., 2024). Since the methodology for environmental performance analysis is still under development and foresees complex test procedures, this latter part will not be treated in this work.

MATERIALS AND METHODS

Component performance

The most important aspects of performance considered are the drop size distribution (DSD) from nozzles and the vertical distribution of air from the air distribution system. These aspects are important as they are directly responsible for the spatial distribution of PPP and its deposition on the canopy of trees.

The sprayer employed in these sample tests is a model 10 81 VV-HS (Mitterer Professional Sprayers, Terlan, Italy), to be seen in Fig. 1, left. The sprayer has an 810 mm diameter axial fan, able to produce airflows up to a 64000 m^3h^{-1}, and tower-shaped air distribution system. The sprayer was equipped with two sets of CVI 80 nozzles (Albuz® Spray, Evreux Cedex, France) class 025 and 050. For a detailed explanation of nozzle size classification, see (ASABE, 2020).

Figure 1. The employed sprayer (left). Notice the top deflector at the upper end of the distribution system. On the right is a detail of its air distribution system with the WP5000 sensing array.

The air distribution was tested by a dedicated test bench, model WP5000 (Ernst Herbst Prüftechnik e.K., Hirschbach, Germany). The instrument, to be seen in Figure 1, right, and methodology are detailed in (Becce et al., in press). Quoting, "*the device is based on an array* *of five equally spaced ultrasonic triaxial anemometers mounted on a moving frame capable of translating horizontally and vertically. The sensors can scan across 1.9 m in horizontal, in the direction the sprayer would advance in, and from 0.3 m up to 5 m in vertical. The scanning resolution is […] 0.1 m in each direction. The sprayer remains stationary during the tests, with only the fan(s) running. The spraying system remains deactivated.*" Ultrasonic anemometry for this type of test is growing in popularity in the literature, due to its relatively contained cost and ability to quantify the variations in time of the airspeed (Salas et al., 2022; Salcedo et al., 2015). For the purpose of this presentation, the sprayer air distribution was tested at a single speed, namely 1700 revolutions per minute.

The test bench is tailored to inspection centres operating per predetermined test protocols, so a custom data processing routine is currently under development to extend its functionality, leveraging the raw data collected. The extension keeps in mind the possibility of using the test results in more complex mathematical modelling of spray distribution.

The presented data will be treated as per the default process: defining a threshold to distinguish "between usable air[flow] (that is, fast enough to penetrate the canopy) and non-usable air[flow]" [*ibidem*]. A "working height", that is the height of the target canopy, is also set to distinguish between usable and potentially usable air, dispersed above the target canopy.

Functional performance

The vertical distribution of liquid was tested by a vertical patternator, built by Salvarani (Poviglio, RE, Italy). This test bench is a vertical array of surfaces meant to collect the liquid between 0.3 m and 4.5 m high, in 0.1 m increments. The liquid is conveyed to a corresponding measuring tube at the bottom. The tubes allow a quick visual inspection of where the most liquid is delivered: the distribution pattern from a properly regulated machine should ideally match the density of the target canopy. The patternator, can be seen in Figure 2, left.

Figure 2. The sprayer during a deposition test on the vertical patternator (left) and a detailed view of the patternator (right). The collecting surfaces in black convey the liquid to the graduated tubes at the bottom.

As provided, the system suits very well any training and field calibration needs; but for research and comparison purposes, a more repeatable approach has to be deployed.

The volumes collected across three test repetitions are recorded and normalised against the sum of collected volumes. As explained in the user manual of the vertical patternator, a symmetry index *S* between left (L) and right (R) side can be calculated as:

$$S\,[\%] = 100 - \sum_i \left| v_{L,i} - v_{R,i} \right| \tag{1}$$

where $v_{L/R,i}$ is the measured volume from each side in the tube i, the normalised against the total collected volume per side.

The sprayer was tested in two configurations at the same fan speed of 1200 min^{-1}, differing in the nozzle size and liquid pressure, being these size 025 (ISO colour lilac) at 1.2 MPa and size 050 (ISO colour brown) at 1.1 MPa. These parameters were derived from the user manual to simulate a treatment on early-stage and full-bloom vegetation, respectively.

RESULTS AND DISCUSSION

Component performance: air flow distribution

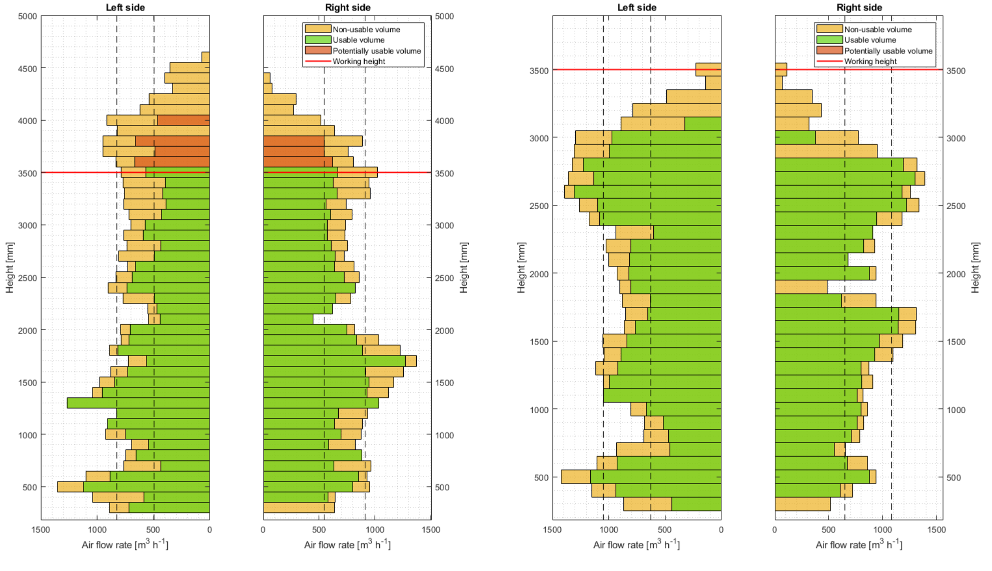

Figure 3. Air distribution from the two configurations: top deflector high (left) and low (right). The red line marks the same height of 3.5 m from the ground. The dashed lines represent the mean ± 25% usable flow rate for each side, to qualitatively visualise what would be a uniform distribution. The green area represents the usable airflow, yellow the non usable and red the potentially usable.

The results of the air distribution testing appear in Figure 3. The only differing factor is the position of the top deflector, while the fan speed was kept constant at about 1700 min^{-1}. The yellow areas represent the total air flow, while the green and red are air flows blown at a speed sufficient to penetrate the canopy: the latter, however, is distributed above the ideal canopy, and is therefore a waste on energy and a potential source of drift.

Predictably, the air conveyed toward the top when the deflector is held high (left in the figure) is concentrated slightly below, with *de facto* little to no usable air being distributed above 3 m (right in the figure).

The total flow rate of the “high” configuration was 68174 m^3h^{-1}, of which 45155 m^3h^{-1} (66.2%) usable. The figures are not substantially different for the “low” case, with 60007 m^3h^{-1} total and 45965 m^3h^{-1} (76.6%) usable, almost the same as the other case. The L/R divergence in the usable flow is contained, amounting to 7% (“high”) and 10.9% (“low”).

These figures indicates a good design of the distribution system, in that the intervention of a deflector does not induce substantial energy dissipations that would slow the air down.

Functional performance: vertical deposition pattern

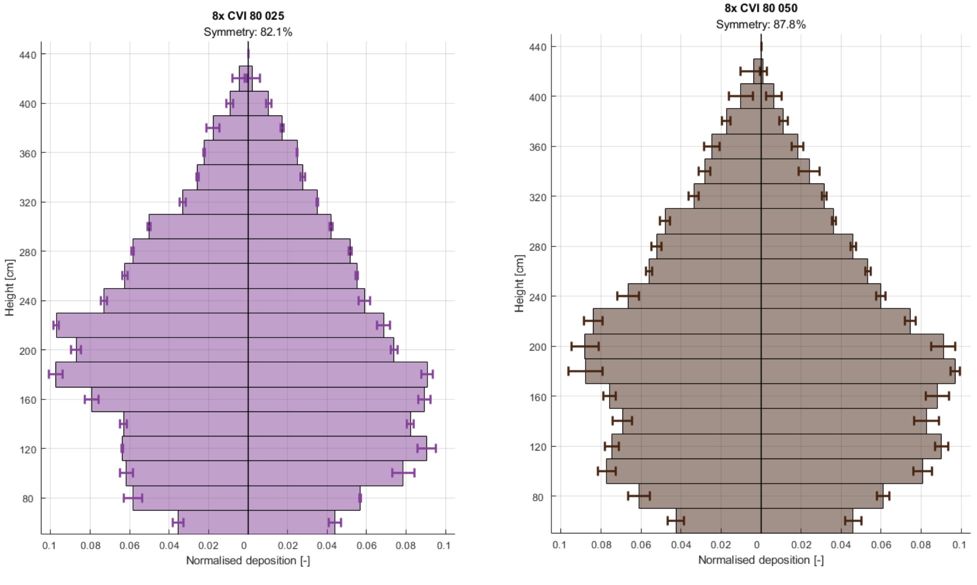

Figure 4. Results of the vertical deposition tests with the two nozzle types: 025 (left) and 050 (right). The deposition is normalised against the total collected volume. The error bars represent the standard deviation among 3 test repetitions.

Figure 4 presents the deposition patterns from the machine in the two tested configurations. Given the high similarity of the patterns, it is evident that the single components work as intended. Should the target plant canopy differ in shape from the profile, the overall distribution pattern could be better adapted by iteratively orienting the nozzles.

The joint analysis of airflow rate and liquid distribution can yield a further insight: Fig. 3, left, is referred to a similar configuration (top deflector held high); if comparing the liquid distribution with the air flow one, whose shape is much more regular, one can conclude that, in order to make the liquid distribution more regular, the adjustment should concern the position and direction of the nozzles.

CONCLUSIONS

This paper introduced the vision of the "technological chain", a systemic approach to break down the performance of sprayers based on the level of detail sought. This point of view enables to clearly separate the different variables involved in the problem of administering plant protection products and investigate the relationships between the single involved phenomena. Two examples of the application of this view have been given, analysing the performance of a single component (the air distribution system) and the liquid distribution pattern of the machine, which is the result of the interaction of air flow and liquid distribution from the nozzles. Based on the results of the single analyses, some insight into which factors are affecting the overall ("functional") performance have been drawn.

From a systems engineering perspective, regardless of how eloquent the data from the single tests can be, the integration of different links in the chain must be sought (that is, different levels of detail). An interesting approach can be mathematical modeling, integrating data from single tests and instruments to build a wider understanding of the interactions between the single variables.

This widened vision can have beneficial implications on all stakeholders involved: from the sensibilisation of end-users, through the support to research & development, to better informed decision-making.

End users, that is machine operators, can gain a wider understanding of the importance of each variable that they have control over when operating a sprayer, enabling better treatments while raising their awareness of the importance of a well performed treatment.

Manufacturers can gain interesting insight into improving and optimising their machines, while handing out accurate recommendations to their users.

Inspection and certification centres can test the sprayers in a more reliable way, reducing the need for field tests under conditions which are often too unpredictable, with consequent increases in times and costs of testing.

Finally, decision-makers can draw aggregated information on the consequences of plant protection campaigns and be supported toward a more agile development of down-to-earth policies and recommendations.

ACKNOWLEDGEMENTS

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50. ACTUAL TASKS ON AGRICULTURAL ENGINEERING

Preliminary communication

AUTOMATED MONITORING OF SPRAY DOSING PROCESS IN THE VINEYARD

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ABSTRACT

In this study, the researchers presented an automated modular system for a controlled spray mixture process in the vineyard, monitoring via IoT technology in real-time. With an automated modular system, it is ensured the optimal dosage rate of the amounts of the spray mixture on the vine canopy. The IoT module enables the remote capture of the amount of spray mixture savings by individual nozzles of the automated sprayer prototype in [%]. A comparison of the spray process was made between conventional and automated sprayer operation mode. The key results achieved in the automated process of applying the spray mixture is the testing of the automated modular system, mounted on a conventional sprayer type. The total savings for four consecutive automated mixture processes was 557.70 Lha^{-1}, for the left side of the sprayer and 514.15 Lha^{-1}, for the right side of the sprayer. The total plant production product savings in [EUR], for the left side of the sprayer, was 201.63 EURha^{-1} and for the right side, 183.90 EURha^{-1}. Results show that spraying in automated mode, where we reduce the dose of spray mixture because of a lower density of green wall, causes a reduction in the efficacy of disease control.

Key words: *vineyard, monitoring, IoT technology, spraying process, automation, grape production*

INTRODUCTION

Farmers in the agricultural sector have been able to greatly increase the productivity of food production throughout the world over the past few decades; fruits and vegetables, at the expense of the use of plant protection products (PPP), without experiencing significant crop losses due to pests, weeds and diseases (Ghimire and Woodward, 2013). Researchers (Sharma et al., 2019) found that 2 million tons of PPP are used worldwide, of which 47.50 % are herbicides, 29.50 % insecticides, 17.50 % fungicides and 5.50 % other pesticides. According to the farm accountancy data network (FADN) of the EU, PPP represents one of the most important economic factors in agriculture, which represents up to 12.50 % of the total costs in the production of agricultural products in some regions of the EU. However, the use of PPP has harmful consequences for human health and the environment in which we live (Aktar and Sengupta, 2009). Excessive use of PPP's has little value and has negative consequences for the ecosystem, such as resistance to PPP's, damage to the genetic structure of living organisms and reduction of biodiversity (Ghimire and Woodward, 2013). Therefore, it is crucial to reduce not only the improper use of PPP, but also the overall consumption of PPP (Anastasiou et al., 2023).

Precision viticulture in conjunction with other agricultural processes (such as integrated pest management, crop rotation, physical or mechanical control and microbiological control), can help in reducing the total consumption of PPP's in the world (Grella et al., 2023). Precision farming is a strategy of controlling various work processes, which focuses on observation (one might say almost in real time), measuring and responding to variability in crops, fields and animal control using many different modern technologies (Anastasiou et al., 2023). Precision farming can help increase yields and animal productivity, as well as reduce costs, including labor costs, and optimize the use of process inputs. All this can contribute to greater profitability in various agricultural industries. At the same time, precision farming can improve worker safety and reduces the impact of agriculture on the environment and farming methods, which also contributes to the sustainability of agricultural production. As a result, using precision farming technologies (PFTs) for PPP prediction, early detection, and pest control can drastically cut pesticide consumption (Marković et al., 2021). With modern laser LIDAR (Light Detection and Ranging) measurement technology, we can provide information regarding the geometric characteristic properties of canopies in orchards and vineyards (Moreno et al., 2020; Petrović et al., 2022). Through the modern Internet of Things (IoT), technologies can help in the prediction and detection of PPP and diseases (Pathmudi et al., 2023).

Vineyard management system helps in remote monitoring of vineyards in combination with electronic and software platforms. Wireless sensor networks, so-called IoT modules are installed in the vineyard that collect microclimate data, soil data and plant physical condition. The collected data is presented on the control panel in the form of interactive visual displays to obtain valuable insights/information that winegrowers can use in making important decisions to improve work processes in the vineyards. The emergence of IoT technology has created a lot of buzz in the past few years. Almost every industry has adopted it or is in the process of adopting IoT. In the agricultural industry, especially winegrowers, they are very eager to adopt IoT technology and take advantage of its use in the vineyard. However, by using IoT technology in vineyards, winegrowers can collect microclimatic data such as temperature, humidity, rainfall, wind speed, soil moisture, etc., which help in protecting grapes from the aforementioned adverse atmospheric conditions. The collected data is mainly used for purposes such as improving the quality of grapes, increasing the amount of grapes (yield) and reducing the risk of disease outbreaks (leaves, grapes).

MATERIAL AND METHODS

The vineyard of the agricultural holding Miha Toplišek, Gostinca 18, 3261 Lesično, Slovenija were used for the experimental proposal. The area of the vineyard for the experiment was 2000 m^2, the location of the experiment is 46°07'27.2"N 15°32'04.3"E (Figure 1). In the intensive vineyard (Welschriesling variety) at the age of 6 years, they are planted on the basis of kober 5bb. The base 'kober 5bb' shows very good compatibility with the variety 'Welschriesling', and good compatibility with the varieties 'Furmint', 'Rhein Riesling' and 'Sauvignon-sauvignon-blanc'. The base is used in individual wine-growing regions of Slovenia and was selected according to professional criteria. The inter-row distance between seedlings is 230 cm and the vines are planted in a row at a distance of 100 cm. The cultivation method was single-spar cultivation (spar with up to ten eyes) with plug (one to two eyes on the plug), whereby the height of the vine stem is 90 cm. During the season of the spray mixture application process, we carried out 4 mixture treatments via the modular automated system mounted on a conventional sprayer type (Figure 1).

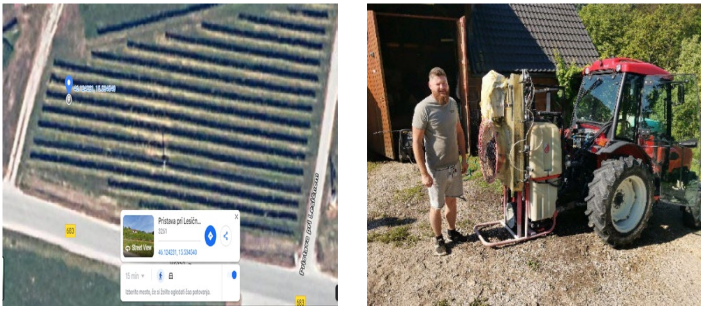

Figure 1. Automated application process testing location and real-time monitoring of spray mixture dosage on conventional sprayer

Modular automated systems for continuous control and monitoring of spray mixture dosage in real-time were installed on a conventional axial type of sprayer manufacturer (Agromehanika, Kranj, Slovenia) and tested it under real conditions in the vineyard. The modular system was used to control the optimal dosage of the spray mixture on three segments of the left and right halves of the vine canopy, according to the size of the density of the green leaf wall area, which is digitally defined using laser measurement technology (Petrović et al., 2022). Continuous control of consumption of spray mixture dosage amounts (in the range from 0% to 100%) through individual nozzles via electromagnetic valves took place in the modern pulse width mode (PWM) operation (Figure 2a). Compared to previous years, the automated modular system was upgraded with an IoT module (Figure 2b) and put in a metal box with IP65 protection. With the help of the IoT module, we made it possible to capture and display the dosage rate of spray mixture through the individual nozzles on the left and right half of the sprayer set, namely on a special table on the website.

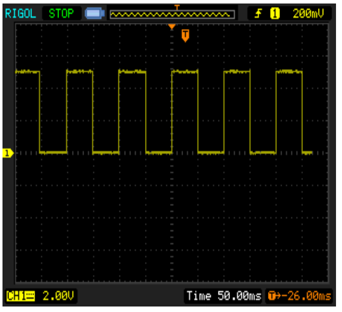

Figure 2a. PWM control of EMV

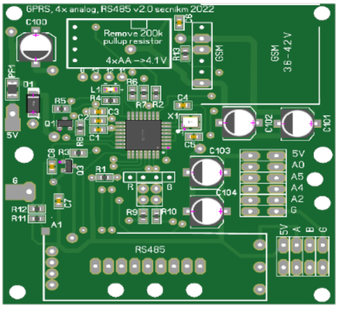

Figure 2b. IoT electronic modul for spray mixture dosage rate monitoring

An automated sprayer prototype was installed to a fruit-growing tractor, where the average speed of movement of the sprayer during spraying was 4.0 kmh-1. The following type of nozzle was used on the sprayer: Lechler, yellow TR, 80-02, at a pressure of 10 bar, with a dosage rate of 1.45 Lmin-1. For automated control of spray mixture dosage on three segments of the vine canopy, we have used 3/2 NC-solid valve with 3 connections on the housing, nominal power of the coil 7 W). The operation of EMV took place in direct mode, which means that in the case of a DC supply voltage of 12 V, which is applied to the electromagnetic coil of the valve, enables the open state of the EMV. In the experiment in the vineyard, were used a LIDAR LMS111 laser measurement sensor (manufacturer SICK AG Waldkirch, Germany), which represented a component for measuring two polar coordinates (distance, polar angle). The LMS111 lidar offers an excellent compromise between compact size and performance. It enables data capture at a frequency of 50 Hz and an angular resolution of 0.5°. Its reach is up to 20 m. Data transfer takes place in real time via an ethernet interface with a nominal speed of 100 Mbit/s. With lidar measurement technology, we have made it possible to digitally reconstruct the characteristic features (size of the density of the leaf wall area) of the vine canopy, namely for different phenological stages of the vine, which effect on the consumption of spray mixture dosage rates (Berk et al., 2019).

The IoT module consists of the following components; AtMega 328p microchip and GSM/GPRS SIM800L components. The high-performance Microchip picoPower® 8-bit AVR® RISC-based microcontroller AtMega 328p combines 32 KB ISP Flash memory with read-while-write capabilities, 1024B EEPROM, 2 KB SRAM, 23 general purpose I/O lines, 32 general purpose working registers. The SIM800L GSM/GPRS component is a miniature GSM component that can be used in a variety of IoT projects. The IoT module, which represents an upgrade of the automated modular system for the automated process of applying the spray mixture dosages in the vineyard, every 5 seconds, reports the average dosage rate through the individual nozzles. The task of the IoT module is to capture data on the dosage rate through the nozzles and send it to the SQL database via the GSM network. Then the automated system allows us to transfer and display the data about the mixture dosage rate in real-time on the website.

RESULTS AND DISCUSSION

Among the key results achieved in the automated process of applying the spray mixture is the testing of the automated modular system, mounted on a conventional sprayer type AGP

200 (manufacturer Agromehanika, Kranj, Slovenia). Through the modular system, which in the vineyard in real time, enabled continuous control of spray mixture dosage rate amounts on the green leaf wall area and implemented monitoring via IoT technology. Continuous control of the dosage rate of the mixture took place via EMV which operates in the PWM. Monitoring of consumption of dosage rate through individual nozzles for the left and right half of the sprayer set is available on the website: *https://4759.eu/UM/Sprayer/dataSprayer.php* in the form of a table. Table 1 shows the spraying program which we used to control diseases (downy mildew and vine oidium) in the vineyard, integrated grape production.

Table 1. Technological instructions (spraying program), which we used to control diseases in the vineyard during the season of regular spraying processes, year 2024

Integrated grape production	**Spray program**	**Date of spray application**
Vineyard producer Miha Toplišek	Folpan Gold: 80 g/200 L Pepelin: 1 kg/200 L Basfoliar: 1 L/200 L Nu Film: 1 dL/200 L	09.05.2024
Vineyard producer Miha Toplišek	Folpan Gold: 80 g/200 L Pepelin: 1kg/200 L Basfoliar: 1 L/200 L Nu Film: 1 dL/200 L	18.05.2024
Vineyard producer Miha Toplišek	Folpan Gold: 80 g/200 L Pepelin: 1,5 kg/200 L Ortus 5 SC: 3 dL/200 L	25.05.2024
Vineyard producer Miha Toplišek	Orvego: 1 L/200 L Collis: 6 dL/200 L Nutribor: 2,1 kg/200 L	05.06.2024

In the vineyard experiment, we determined the size of the dosages of spray mixture in the first, conventional mode of operation of the sprayer, which we applied on the green leaf wall area of the vine, via an empirical model (i.e. classic hectare dose). In the second, automated mode of operation of the sprayer, the spray mixture dosage was controlled according to the digital size of the density of the leaf wall area of the vine canopy (Berk et al., 2021). Table 2 shows the results of spray savings in [%], when the sprayer was operating in automated mode. In order to properly optimize the operation of the application spray process, we were conducting individual field experiments using a different number of nozzles. Different numbers of nozzles on an automated sprayer prototype were activated depending on the size of phenological growth stage of the vine. Table 3 shows the PPP savings analysis in [EUR] for the left and right sides of the automated sprayer prototype.

Table 2. Comparative analysis between automated and conventional sprayer operation mode in terms of spray dosage consumption, year 2024

Date of spray application	Nozzle 1 dosage savings [%]	Nozzle 2 dosage savings [%]	Nozzle 3 dosage savings [%]	Average dosage savings on the left side of the automated sprayer [%]	Average dosage savings on the left side of the automated sprayer [L ha^{-1}]	Conventio-nal spray mixture dosage [L ha^{-1}]
09.05.2024	53.85	81.47	No active	67.66	146.25	216.15
18.05.2024	44.30	72.02	No active	58.16	125.71	216.15
25.05.2024	41.16	64.19	No active	52.68	113.86	216.15
05.06.2024	24.81	52.69	81.54	53.01	171.88	324.22

Date of spray process	Nozzle 1 dosage savings [%]	Nozzle 2 dosage savings [%]	Nozzle 3 dosage savings [%]	Average dosage savings on the right side of the automated sprayer [%]	Average dosage savings on the right side of the automated sprayer [L ha^{-1}]	Conventio-nal spray mixture dosage [L ha^{-1}]
09.05.2024	37.66	71.98	No active	54.82	118.50	216.15
18.05.2024	43.40	70.70	No active	57.05	123.31	216.15
25.05.2024	59.98	40.93	No active	50.46	109.06	216.15
05.06.2024	20.46	48.62	82.00	50.36	163.28	324.22

Table 3 shows the analysis of PPP savings in [EUR], for the left and right side of the spray set of the automated sprayer prototype. Analyzes of PPP savings were done separately, for each spray mixture application process in the growing season 2024. By analyzing dosage savings, we took into account the spraying program of Miha Toplišek's farm, through the regular spraying season.

The automated spray process in the vineyard was tested four times during the season, whereby we activated a different number of nozzles. Four nozzles were used for the first three spray processes namely, two nozzles each on the left and right side of the automated sprayer prototype. In the last fourth process, six nozzles were activated, three each on the left and right half of the sprayer set (see color codes in table 2). Total savings for four consecutive automated mixture processes was 557.70 Lha^{-1}, for the left side of the sprayer and 514.15 Lha^{-1}, for the right side of the sprayer. The total PPP savings in [EUR], for the left side of the sprayer, was 201.63 EURha^{-1} and for the right side 183.90 EURha^{-1}.

Spraying was done in two sprayer setting modes, with and without sensor-guided dosing of the amount of spray per hectare. Plots with the first or second sensor operation mode were divided into four sub-plots. Diseases infestation rate analysis was done according to EPPO (European Plant Protection Organisation) standards by direct visual scouting of % infestation area of leaves or grape clusters. 200 randomly chosen leaves or grape clusters were assessed per plot by several teams a season.

Table 3. Analysis of PPP savings in [EUR], for the left and right half of the sprayer set

Date of spray application	PPP	PPP packaging	PPP price [EUR]	PPP dosage	PPP price [EURh^{-1}]	PPP savings left side of automated sprayer [EUR]	PPP savings right side of automated sprayer [EUR]
09.05.2024	Folpan Gold	1 kg	18.60	2.5 kgha^{-1}	46.50	15.73	12.75
	Pepelin	1 kg	15.00	5 kgha^{-1}	75.00	25.37	20.56
	Basfoliar	1 L	22.90	3 Lha^{-1}	68.70	23.24	18.83
	Nu Film	1 L	37.44	0.5 Lha^{-1}	18.72	6.33	5.13

Date of spray application	PPP	PPP packaging	PPP price [EUR]	PPP dosage	PPP price [EURh^{-1}]	PPP savings left side of automated sprayer [EUR]	PPP savings right side of automated sprayer [EUR]
18.05.2024	Folpan Gold	1 kg	18.60	2.5 kgha^{-1}	46.50	13.52	13.26
	Pepelin	1 kg	15.00	5 kgha^{-1}	75.00	21.81	21.39
	Basfoliar	1 L	22.90	3 Lha^{-1}	68.70	19.98	19.60
	Nu Film	1 L	37.44	0.5 Lha^{-1}	18.72	5.44	5.34

Date of spray application	PPP	PPP packaging	PPP price [EUR]	PPP dosage	PPP price [EURh^{-1}]	PPP savings left side of automated sprayer [EUR]	PPP savings right side of automated sprayer [EUR]
25.05.2024	Folpan Gold	1 kg	18.60	2.5 kgha^{-1}	46.50	12.25	11.73
	Pepelin	1 kg	15.00	5 kgha^{-1}	75.00	19.75	18.92
	Ortus 5 SC	1 L	51.00	1 Lha^{-1}	51.00	13.43	12.87

Date of spray application	PPP	PPP packaging	PPP price [EUR]	PPP dosage	PPP price [EURh^{-1}]	PPP savings left side of automated sprayer [EUR]	PPP savings right side of automated sprayer [EUR]
05.06.2024	Orvego	1 L	60.00	0.8 Lha^{-1}	48.00	12.72	12.09
	Collis	1 L	58.00	0.4 Lha^{-1}	23.20	6.15	5.84
	Nutribor	1 kg	11.11	2 kgha^{-1}	22.22	5.89	5.59

The followed EPPO standards were: PP1/4(4) *Uncinula necator*, PP1/17(3) - *Botryotinia fuckeliana* on grapevine and PP1/31(3) – *Plasmopara viticola*. The rate of fungal attack on leaves and grape clusters was assessed by visual scouting of % diseased area (Table 4). 200 leaves and 200 grape clusters were evaluated on each sub-plot. Leaves and grape clusters were randomly chosen in different parts of the grape-green wall.

Table 4. Attack rate of downy mildew (*Plasmopara viticola*) and powdery mildew (*Erysiphe necator*). Assessment was done on the 18th of July.

Variant	*Plasmopara viticola*		*Erysiphe necator*	
	% infected surface area of leaf	% infected surface area of bunches	% infected surface area of leaf	% infected surface area of bunches
Spraying without sensor-guided dosing of spray (100 % pesticide dose)	11,40 ± 2,28 b	7,50 ± 0,29 b	4,20 ± 0,60 b	0,70 ± 0,05 b
Spraying with sensor-guided dosing of spray (reduced pesticide dose)	18,03 ± 4,32 a	12,62 ± 1,10 a	7,10 ± 1,02 a	3,22 ± 0,16 a

Values marked with the same letter do not differ statistically significantly according to the Tukey HSD test ($P<0.05$).

Results show that spraying in automated mode, where we reduce the dose of PPP because of a lower density of green wall, causes a reduction in the efficacy of disease control. Increase in the diseased area of leaves and grapes is not very big but is statistically significant when compared to grapes sprayed in the automated mode. The difference in fungal attack rate between both spray dose control modes also depends on the spraying frequency and biological efficacy of used PPP. If spray frequency is low and we use less efficient PPP, the difference will be more significant.

CONCLUSIONS

Various researchers have shown reports on the amount of PPP savings during precision spraying. There is, however, much less evidence on how much the PPP savings affect the efficacy of disease control. We have shown, that dosage savings in excess of 50 % indeed decrease the efficacy of disease control, although not by a very large margin. We expect that further improvement through dedicated research is still possible, including operation of valves in PWM mode, IoT technology and in interaction of the plant, disease and spray distribution, etc. In the short term, IoT technology may provide the possibility to quickly and efficiently evaluate results of spraying on a tree to tree basis. Novel analysis methods may also provide useful insights into the relationship between the number of PPP savings, emerging diseases, efficacy of disease control and yield.

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50. ACTUAL TASKS ON AGRICULTURAL ENGINEERING

Preliminary communication

DESCRIPTION OF THE AGRO-BIOLOGICAL CHARACTERISTICS ON DIFFERENT GENOTYPES OF SAFFLOWER

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ABSTRACT

*Recent climate changes are impacting crop plant yields. In this context, the aim is to enrich plant collections by: saving endangered species, expanding the cultivation of valuable local species/populations, and improving and adapting cultivation technologies to new field conditions. In this preliminary study, two varieties of Safflower (*Carthamus tinctorius *L., fam.* Asteraceae*) with different origins were analyzed. One spiny variety included two local populations from the Moldavian Plain area (Botoșani and Bacău), and a spineless variety included two local populations from the Romanian Plain (Teleorman and Călărași areas).*

The main objective of this study was to evaluate the biological potential of these genotypes cultivated in the southeastern part of the country during the 2024 growing season. This season was characterized as the warmest and driest throughout the observation period. Temperatures were 2.5 to 3.3 ºC higher than usual, with prolonged drought periods and extremely low rainfall amounts (100 - 250 mm below the period's average). Observations were made regarding the phenological development stages of the plants, as well as the main characteristics of the inflorescences in the two safflower varieties. The results obtained will serve as a practical foundation for the reintroduction of this valuable plant species into cultivation.

Keywords: *biodiversity conservation, safflower, local populations, inflorescence characteristics*

INTRODUCTION

Safflower (*Carthamus tinctorius* L., fam. *Asteraceae*) is an annual, multifunctional, yet underutilized and neglected plant that is drought, heat, cold, and salt tolerant, with numerous applications in the food, textile, and pharmaceutical industries, among others. Safflower belongs to the group of oilseed plants, from which a high-quality oil is extracted. This oil is used in human nutrition, either on its own or in blends with other vegetable oils, increasing their stability, shelf life, and quality due to its high linoleic acid content (over 75%) (Tabără, 2005). Interest in cultivating safflower has recently grown significantly due to its drought tolerance, increased demand for biodiesel, and consumer preference for healthy oil rich in unsaturated fats and low in saturated fats, as well as for natural dyes used across various industries, including cosmetics and pharmaceuticals. The identification of safflower oil as a rich source of essential fatty acids: linoleic (polyunsaturated) and oleic (monounsaturated) has further amplified interest in cultivating this species. In semi-arid and arid regions, affected by salinity and reduced rainfall due to climate change, safflower can yield good seed production. Thanks to its genetic diversity, safflower is a climate-smart crop that can easily adapt to variable environmental conditions. Effective implementation of support policies regarding technological inputs, pricing, and marketing by countries facing water scarcity and salinity could significantly enhance food security, reduce poverty, and increase income and livelihoods for farmers in these countries (Emongor and Emongor, 2023).

In Romania, safflower is part of the species with a "*broad biodiversity portfolio*" but is underutilized for commercial cultivation. Safflower offers a viable agricultural alternative to sunflower crops, being suited for less fertile, marginal lands. Saffron's water tolerance sets it apart from other oilseed crops, such as sunflower and particularly rapeseed, which require constant water (Ivan and Tudora, 2014; Nasiyev et al., 2022). Although the crop is less demanding regarding soil quality and thrives on poorer soils and in wetter areas, it is still not cultivated and utilized as widely as sunflower. This species, naturally well-adapted to dry and warm conditions, can be cultivated in southern and southeastern regions of the country (Tudora et al., 2024). It is worth noting that in Romania's "*biodiversity heritage*," the "wild relative" of cultivated safflower, *Carthamus lanatus* L., also known as Woolly distaff thistle, is found in the spontaneous flora (figure 1).

Figure 1. Woolly distaff thistle (*Carthamus lanatus* L.)

Woolly distaff thistle (figure1) is an annual species, reaching heights of 25-100 cm, with yellow flowers. The plants are lanate and cobweb-hairy, with external involucrate folioles, linear-lanceolate in shape, with strong spines. The pappus of the achene is multiseriate, with the outer series being squamiform and the other series successively longer. It grows sporadically from the plains up to the oak region, on pastures, rocky and sunny slopes, in ruderal areas, and on calcareous soils (Cristea and Murariu, 2018). Using biodiversity to create new varieties that are resilient to high temperatures or drought could help farmers cope with the effects of climate change, enabling them to cultivate crops in harsher conditions. Recent studies have found that by 2055, more than half of the 43 agricultural crops studied (grains such as wheat, rye, and oats, etc.) will lose suitable land for cultivation (FSC Guide). Wild relatives of these crops, an important source of diversity, are also at risk. Scientists have used modeling to predict the impact of climate change on the wild relatives of key food crops. They have determined that within the next 50 years, no less than 61% of the 51 wild peanut species and 12% of the 108 wild potato species could become endangered due to climate change (FSC Guide).

The cultivation potential of safflower is quite high, yet in our country, there are few cultivated areas due to the lack of information about this crop. Additionally, the unavailability of the necessary biological material for sowing results in a lack of interest among growers. However, in recent years, interest in this crop has grown due to its advantages:

- consumer preference for healthy oil with lower saturated fat content, for which safflower is well-known;
- increasingly pronounced drought and precipitation scarcity recorded in recent years, resulting in a major seed oil production deficit, with safflower able to thrive under limited water availability;
- the plant's medicinal properties and the extraction of edible dyes from its flowers;
- processing and obtaining high-value-added products from safflower (seed oil, dye from petals) and its use with new, specialized equipment for harvesting inflorescences/petals (Muscalu et al., 2023);
- promotion of safflower cultivation through farmer training on crop technology.

The main objective of this study was to evaluate the biological potential of 4 local Romanian safflower populations, cultivated in the southeastern part of the country and to obtain petals as raw material for future investigations.

MATERIAL AND METHODS

The plant material consisted of seeds from 4 Romanian sources of safflower (*Carthamus tinctorius* L., fam. *Asteraceae*), which are part of the Germplasm Resource Collection of the "*Mihai Cristea"* Plant Genetic Resources Bank in Suceava. The local populations represent those crop populations that are in equilibrium with their native environment and remain relatively stable over a long period. These local populations belong to 2 different varieties:

- "*Spiny*" safflower:

  Local population from Botoșani, Dorohoi, L1 - BT;
  Local population from Bacău, Oncești, L2 - BC;
- "*Spineless*" safflower:

  Local population from Teleorman, Teleormanu, L3 - TR;
  Local population from Călărași, INCDA Fundulea, L4 - CL.

For each line, packets containing 50 seeds were received (figure 2).

L1 - BT L2 - BC L3 - TR L4 - CL

Figure 2. Biological material (4 local populations Romanian safflower)

The experimental field layout for the 4 lines was set in the Bucharest-Băneasa area (lat. 44º30'01"N, long. 26º04'19"E, alt. 90 m), under the climate conditions of 2024, on a reddish-brown forest soil over a 50 m² area.

The cultivation technology used included the following steps:

Crop rotation - safflower is cultivated following crops such as cereals and row crops. It is not recommended to grow safflower after crops attacked by nematodes (oats, sugar beets, potatoes, and tobacco). By simply rotating crop species, the cycle of certain diseases and pests is disrupted, reducing the probability of infestation. In this case, the crop was established after a preceding crop of white mustard (green manure) sown in the spring of 2023, which was then cut, shredded, and left on the soil surface. This approach maintained soil moisture over the summer, and the field was clean and free of weeds. Mustard was chosen as the preceding plant (figure 3) due to its advantages:

- an annual plant with a short growing season, drought resistant, and repellent to nematodes;
- a plant with a deep, strong root system that aids in aerating and loosening the soil;
- its robust root system plays a significant role in preventing erosion, helping to protect the land and maintain long-term soil fertility;
- a fast-growing plant with a high nutrient content; left to decompose (as in this case), it enriches the soil composition with organic matter and nutrients (N).

Figure 3. Mustard crop (*Sinapis alba*, fam. *Brassicaceae*)

Fertilization – in the conditions at INMA Bucharest, no fertilization was done during the growing season. However, the preceding crop (mustard), sown as green manure, left 55 kg N active substance in the soil (figure 3).

Soil preparation – deep plowing was performed at a depth of 22-25 cm. The seedbed was prepared the day before sowing using a harrow, to ensure the soil was well-leveled, achieving good soil fragmentation to a working depth of 5 cm.

Sowing – the crop was established by direct field sowing using 2 planting times:

- autumn, in the first ten days of October 2023;
- spring, in the first ten days of April 2024.

Four rows (corresponding to the 4 safflower lines) were sown manually in a pattern of 50 cm × 35 cm, at a depth of 5 cm, with 25 seeds per row. The same sowing pattern was used in spring. According to data from INMH, the agro-meteorological parameters on the sowing day were:

Table 1. Agro-meteorological data (October 2023)

Air temperature (ºC)	3.88 ºC
Soil moisture (%)	11.7 %
Soil temperature (ºC)	3.3 ºC
Dew point	3.80
Relative air humidity (%)	99.96 %
Wind speed (m/s)	2 m/s
Atmospheric pressure (mm Hg)	752 mm Hg

Maintenance – during the growing season, the soil was kept weed-free through manual hoeing and weeding whenever necessary. Weed control was done with two manual hoeings at 15day intervals. The first hoeing was carried out immediately after emergence (when the rows were already visible), and the second when the plants were in the rosette stage, a critical period when the crop is sensitive to weed infestation. After emergence, in the rosette stage, safflower can withstand temperatures of -4 to -7 °C for a short period. It is noteworthy that after sowing, to hasten seed germination in the dry soil, irrigation was done using a drip system.

Harvesting and processing – the optimal time for harvest is when the seeds are white and matte. The advantage is that the inflorescence does not shed seeds, so they are not eaten by birds. Safflower can be harvested directly from the field with a grain combine in early August. After harvesting, seeds are dried in well-ventilated warehouses, in thin layers. After drying, impurities and foreign materials are removed from the seed mass.

Measurements were made on 10 selected plants, in full bloom, for each Safflower line, to obtain the main characteristics as shown in the table 3. The statistical analysis was performed with the Mathcad 2000 and Excel from MS Office 2007 package.

RESULTS AND DISCUSSION

Immediately after sowing and throughout the entire vegetation period, the main meteorological indicators that influenced germination and the subsequent growth of the plants were monitored. Their monthly evolution (average air temperature – ºC and average precipitation – mm) is shown in figure 4. The recorded data confirm that the spring of 2024 was the warmest spring in Romania (in the period 1901-2024), with a national average temperature of 12.8 °C, surpassing the previous record (spring of 1934), when the national seasonal average temperature was 12.4 °C. In the past two decades, the national average temperature in the spring season has frequently exceeded 11 °C, and the general temperature trend for this season is increasing.

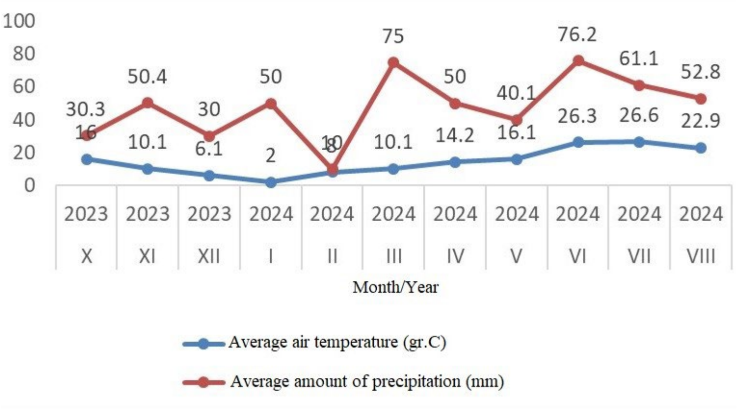

Figure 4. Evolution of main agrometeorological parameters during the growing period

After germination of the white colored achene, weighing between 0.03 and 0.04 g, the seedling passes through the "*rosette stage*," characterized by limited height growth and the emergence of numerous leaves close to the soil level, while a strong root system develops in the soil (figure 5; D1). In this stage, the plant is resistant to cold, even frost, but safflower is less tolerant to fast-growing weeds. During the rosette stage, the growing point of young safflower plants is protected from cold by several layers of young leaves and leaf primordia, so temperatures of -7 °C do not destroy the plant (Dajue, 1996; Kizil et al., 2008). The first leaves that emerge after a frost may show some damage, but the plant recovers and continues to grow normally. After this stage, the stem begins to elongate and gradually branch out (Figure 5; D3, D4). Branches form angles of 30º – 70º with the main stem. Each branch ends in a globular capitulum surrounded by spines (figure 5; D6, D7). The degree of branching in the plant contributes to productivity, so row and plant spacing should be adjusted based on this trait. In mature plants, the main root can reach a depth of 2 - 3m in the soil, with numerous secondary, lateral roots. Due to this root system, safflower is particularly drought-resistant and can be cultivated without issues in areas lacking irrigation systems. In a study conducted by Cintia et al., 2024, on the effects of water deficit in safflower at different phenological stages, results showed that production-related elements (number of capitulum, number of seeds, and seed weight) increase when plants receive water during the vegetative and reproductive (grain-forming) stages. Conversely, water availability only during the vegetative stage results in decreased yield for these components. Regarding excess water, received in all phenological stages, plant height and stem diameter are compromised, indicating that safflower does not tolerate excessive moisture. No disease or pest attacks were reported in this crop during the growing season.

Figure 5. Phenological stages of Safflower (Carthamus tinctorius L.): D1 - vegetative stage, D2 - inflorescence differentiation, D3, D4 - lateral branching, D5 - reproductive stage, D6 - stem harvest timing, D7 - full flowering, D8 - seed formation, D9 - dried flowering stems (adapted from Cintia et al., 2024)

Analysis of results from Table 2, regarding the developmental stages of safflower lines, revealed that:

- The number of days from sowing to emergence was 14 days for L1/L2 (early lines) and 21 days for L3/L4 (late lines). Bătulescu's 1988 doctoral thesis shows that the timing of sowing significantly influences achene yield in safflower. Additionally, Patane et al., 2020, found that delayed sowing (from February to April) significantly decreases inflorescence yield, shortening the growth period due to delayed sowing. Flowering occurs when photoperiod requirements are met (photoperiodic control), regardless of temperature. The same study also showed that early sowing led to a higher pigment content in flowers. Negative relationships between safflower pigments and air temperature indicate that pigment content tends to decrease as temperatures increase during flowering. Plant density had no relevant effect on pigment content.
- Germination was 50-60% for L4 (both sowing dates) and only 16-28% for L2.

- Plant height ranged between 75-80 cm for L1/L2 and 65-70 cm for L3/L4.
- The number of branches (degree of branching in the shrub) per plant is an indicator of productivity and ranged from 16-17 for L1/L2 and 13-15 for L3/L4.

Table 2. Phenological observations regarding the developmental stages of 4 local Safflower populations

	L1-BT	**L2-BC**	**L3-TR**	**L4-CL**
Sowing date	19.10.23 09.04.24	19.10.23 09.04.24	19.10.2309. 04.24	19.10.23 09.04.24
Emergence date	02.11.24 25.04.24	02.11.2425. 04.24	09.11.2425. 04.24	09.11.2425. 04.24
Germination (%)	24/40	16/28	20/40	50/60
Rosette stage	26.04.24	02.06.24	07.05.24	07.05.24
Flower bud stage	02.06.24	28.08.24	17.06.24	17.06.24
Plant height (cm)	75	80	65	70
Branches per plant	16	17	13	15
Flowering date	14.06.24	15.06.24	21.06.24	21.06.24
Fruit date	17.07.24	19.07.24	25.07.24	25.07.24

Observations confirm Omidi-Tabrizi's 2002 study, which reported a positive correlation between the degree of branching and petal yield per plant. Plant height, branch length, and number of seeds per capitulum also directly impact petal yield. High-yielding safflower varieties always have taller lower branches, a longer flowering period, and more seeds.

Figure 6. Diagram of Safflower capitulum characteristics (Li et al, 2023)

Safflower lines reached maturity (Figure 5; D9) after 110 days (L1 and L2) and 130 days (L3 and L4) from sowing. It should be noted that petals, not seeds, were harvested from these 4 safflower lines. Thus, at the end of July, petals were hand-picked, dried, and stored in paper bags. The timing of petal harvest is very important for their yield, though it may affect dye quality. Petal collection and seed harvest can occur simultaneously without significant seed production losses. A study by Kizil et al., 2008, found that the number of branches per plant was significantly affected by the year×variety interaction; however, the petal collection period did not impact oil production.

In this study, during full bloom, measurements were taken on safflower capitula, following the main parameters in the diagram in Figure 6, and the results are shown in Table 3.

Table 3. Characteristics of inflorescences in the 4 Safflower lines (mean± standard deviation)

Type (mm)	L1-BT (yellow, spiny)	L2-BC (yellow, spiny)	L3-TR (red, spineless)	L4-/CL (red, spineless)
Filament diameter (w1)	27.23±1.85	32.37±2.00	33.08±2.10	31.17±2.00
Filament length (w2)	21,41±1.30	21,80±1.70	20,63±1.80	18,61±1.60
Safflower height (w3)	40.10±1.69	42.38±1.80	39.74±1.70	37.20±1.60
Neck diameter (d1)	5,72±0.50	4,91±1.00	5,23±1.00	5,59±1.00
Flower bulb diameter (d2)	17,55±1.85	19,12±2.10	16,86±2.00	16,15±2.10
Flower stem diameter (d3)	3.00±0.21	3.86±0.50	3.31±0.21	3.00±0.30

The analyzed parameters for the two safflower varieties (spiny and spineless) are directly linked to their agricultural potential, in terms of dye content and seed yield. The best results for the spiny variety were achieved with L2-BC, while for the spineless variety, L3-TR stood out. Kizil et al., 2008, in a study on three safflower cultivars from Turkey, showed a direct correlation between w_1 and d_2, which positively influenced the number of seeds per plant, total dye content, and seed production. The filament diameters (w_1) in this study are larger compared to results obtained by Uslu in 2003, which reported values between 18.2-24.5 mm, influenced by environmental conditions. Rajvanshi, 2005, stated that in most spiny safflower varieties cultivated in India, the petal yield available for harvesting was 60-70 kg/ha^{-1}, while spineless varieties had lower yields. The study by Mohammadi and Tavakoli, 2014, showed that if safflower was grown for carthamin production, it was recommended to harvest after pollination when petal wilting began. Conversely, if high levels of carthamidin (yellow pigment) were desired, harvesting should have occurred at the beginning of flowering. Floral stems begin flowering in a yellow coloration, transition to orange with full bloom, and then to senescence with a reddish hue. This color transition from the beginning of flowering to senescence is due to the natural degradation of the oxidative enzyme β-glucosidase present in petals (Menegaes and Nunes, 2020). The factor influencing petal yield is high temperatures during the flowering stage. Uslu in 2003, emphasized that yields were generally higher when daytime temperature at flowering was between 24-32 °C. In terms of dye content, the study by Mohammadi and Tavakoli, 2014, showed that harvest timing affected the amounts of the two dyes: carthamin and carthamidin. Thus, safflower petals produced more carthamidin at the beginning of flowering, which then decreased during full bloom, while carthamin content increased. The quality of safflower raw material depends on growing conditions: air temperature, humidity, soil moisture, sun exposure, and soil fertility. Light intensity affects flavonoid content, with higher synthesis under limited light exposure (Ren et al., 2020). The characteristics of the cultivated plant are also important, and ongoing studies aim to develop safflower varieties with the highest possible pigment content in flower petals (Golkar, 2018).

CONCLUSIONS

As the climate changes, agriculture must rely on a high diversity of crops, the use of locally adapted varieties/populations with high genetic potential, as well as organic fertilizers and biological protection. Choosing varieties/hybrids can pose a major challenge in the face of increasing extreme weather events with growing intensity. Utilizing biodiversity is the key to productive agriculture. Crop diversity provides farmers with options to create, through selection and breeding, new, more productive crops with enhanced nutritional value and resistance to diseases and pests. The results obtained so far from the 4 safflower lines, divided into 2 varieties (spiny and spineless), have shown that they are valuable. They demonstrate resistance to drought in the southeast of the country and have real agricultural potential in terms of dye content and seed production. Future studies will focus on a biochemical evaluation of the petals from these local populations, determining their antioxidant activity and dye content.

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50. ACTUAL TASKS ON AGRICULTURAL ENGINEERING

Original scientific paper

EVALUATION OF THE BIOSTIMULATORY EFFECTS OF NETTLE AND SAGE EXTRACTS ON THE DEVELOPMENT OF GREEN BEANS

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ABSTRACT

Biofertilizers represent an important solution in modern agriculture, contributing to the sustainable growth of agricultural production by improving soil fertility and plant health. Nettle and sage extracts, due to their bioactive compounds, can stimulate photosynthetic processes, increase crop yield, and provide protection against diseases and pests. In this study, nettle (Urtica dioica) and sage (Salvia officinalis) extracts were obtained through ultrasound-assisted extraction. Analyses revealed a polyphenol content of 7.09 ± 0.17 mg GAE/100 g in the nettle extract and 21.51 ± 0.38 mg GAE/100 g in the sage extract, along with high levels of elements such as phosphorus (P), potassium (K), magnesium (Mg), and calcium (Ca), which significantly contribute to plant growth and stress resistance. The analyses revealed a significant polyphenol content in nettle and sage extracts, with a higher concentration in the sage extract. Additionally, these extracts contain high levels of essential elements such as phosphorus, potassium, magnesium, and calcium, which play a crucial role in plant development and enhance their resistance to stress.

Green beans (Phaseolus vulgaris) adapt well to diverse climatic conditions and have high production potential, making them highly valuable in agriculture. The aim of this study is to evaluate the growth of green beans treated with foliar applications of nettle and sage extract mixtures in the following proportions: for experimental plot 1 (L1) – 75% nettle and 25% sage, for experimental plot 2 (L2) – 50% nettle and 50% sage, for experimental plot

3 (L3) – 25% nettle and 75% sage, and experimental plot 4 (L4) – untreated control plants. To determine the effects of these treatments on green bean growth and productivity, chlorophyll content, pod production, and pod dimensions were monitored. Results indicated that treatment L1 recorded the highest chlorophyll content during the monitoring period and produced the highest pod yield.

Keywords: *biofertilizers, green beans, nettle extract, sage extract, plant growth stimulation, extraction*

INTRODUCTION

Growing vegetables naturally, with minimal chemical interventions, is no longer just a trend, but a necessity in modern agriculture. In response to this challenge, scientific research focuses on finding ecological solutions to support farmers and producers in adopting sustainable and environmentally safe practices (Said-Al Ahl et al., 2017).

Green beans are a widely grown and consumed vegetable in many parts of the world, including Romania, due to their nutritional value. They are cultivated in temperate and warm climates, preferring well-drained soils and abundant sunlight. Rich in vitamins C and K, fibers, and antioxidants, they contribute to overall health and are ideal for a balanced diet (Maricic et al., 2022; Kaack, 2018). According to World -Green Beans (2023), in 2023, the global consumption of green beans increased by 1.2%, reaching 25 million tons after two years of decline. This trend is expected to continue, with an annual growth rate of 2%, reaching 29 million tons by 2030. China dominates the market, consuming about 75% of global production. On a per capita basis, the highest consumption was also recorded in China at 13 kg, followed by France (8 kg) and Turkey (6.9 kg) (World -Green Beans-, 2023). According to Sakumona et al. (2023), in Zambia, green beans rank second among staple foods consumed by the population and also in terms of their economic value, playing a significant role in the country's agricultural economy.

Extracts from medicinal and aromatic plants offer an ecological alternative to synthetic products in agriculture due to their bioactive compounds with antifungal and antioxidant effects. These extracts help protect and stimulate crops, improving yield and plant resistance to biotic and abiotic stress, with significant potential for developing sustainable agricultural solutions (Gurgan et al., 2024; Prisa and Menci, 2024; da Silva et al., 2024; Soppelsa et al., 2024; Cenobio-Galindo et al., 2024; Popescu et al., 2015; Zaher et al., 2024; Nenciu et al., 2023). Nettle and sage extracts are recognized for their antifungal, antibacterial, and phytostimulatory properties, providing a natural and effective solution for the protection and healthy growth of agricultural crops (Florez et al., 2022; Durovic et al., 2023; Ahmadi et al., 2014; Mihai et al., 2021; Pruteanu et al, 2018). The study (Maricic et al., 2021) investigated the effects of aqueous nettle extracts on green beans and found that these extracts improved vegetative parameters, such as plant height and stem diameter, and promoted iron accumulation in the leaves (Maricic et al., 2021). In the study (Maricic et al., 2022), the application of nettle extract on green bean plants had beneficial effects, leading to a 49% increase in plant height, a 66% expansion in leaf area, an 11% increase in pod length, and a 48% increase in total yield. Another study (Cerezo et al., 2024) examined the influence of nettle extracts on the disease *Pseudomonas syringae* pv. *phaseolicola*, specific to green beans, and found that the protective effect is due to the antioxidant activity of nettle. This reduced the accumulation of reactive oxygen species (ROS) in tissues, thereby preventing cell damage and enhancing plant resistance to disease. The study (Waked, 2016) evaluated the efficacy of sage extracts against adult pests of *Tetranychus urticae*, recording a mortality rate of up to 92.85% and a significant repellent effect of up to 81.25%. Although the effect on eggs was lower, the extracts prolonged the incubation period and reduced the longevity and fecundity of adult females. The study (Scariot et al., 2016) investigates the insecticidal and repellent effects of *Salvia officinalis* extracts applied to beans, evaluating optimal doses to achieve high mortality rates and insect repellent effects. Results indicate a significant insecticidal effect, with mortality rates exceeding 95% six hours after application, and considerable repellent activity at all doses tested.

The purpose of this experiment is to identify the optimal concentration of nettle and sage extracts that provide the best results on chlorophyll content in plants, green bean crop yield, and pod dimensions, especially length and diameter. The results could support the promotion of biofertilizer use over chemical treatments, as these natural fertilizers, like those from nettle and sage, can reduce environmental impact and improve soil and plant health. This approach may encourage sustainable agricultural practices, ensuring higher quality harvests without harmful chemical residues.

MATERIALS AND METHODS

Nettle and sage extracts were obtained using ultrasound-assisted extraction, a method that utilizes high-frequency ultrasonic waves to create cavitation in the solution, facilitating the breakdown of cell walls and the release of active compounds into the solvent. This ensures faster and more efficient extraction compared to conventional techniques. For sample preparation, 400 g of each type of dried plant, cut into pieces approximately 3 cm in size, were used with 12 liters of solvent (water). Process parameters were as follows: time: 60 min, power: 140 W, amplitude: 20%. The extraction was carried out in a stainless-steel vessel using the Hielscher UP400St equipment (Hielscher Ultrasonics GmbH, UP400St, Teltow, Germany) (Figure 1).

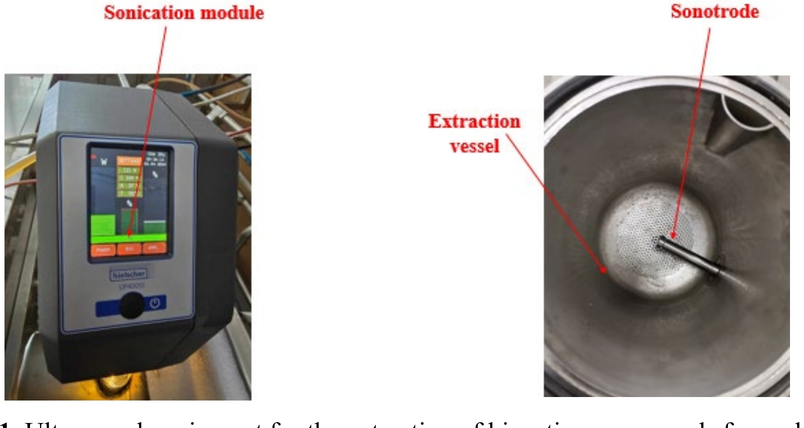

Figure 1. Ultrasound equipment for the extraction of bioactive compounds from plants

The polyphenol content in the obtained extracts was determined using the Folin-Ciocalteu method (Catană, 2021), which involved extracting polyphenols in a methanol-water mixture (1:1), followed by treatment with the Folin-Ciocalteu reagent. The absorbance of the resulting complex was measured at λ=755 nm. The antioxidant capacity of the extracts was determined using the DPPH method, by measuring absorbance at λ=517 nm.

P, K, Mg, Ca elements were determined by spectrometry (Inductively Coupled Plasma Optical Emission Spectrometry, ICP-OES) (Horiba France SAS, Ulltima Expert LT, France). The cultivated green bean variety was *Processor*, known for its high productivity and superior pod quality.

Green beans were planted on July 1st in an area characterized by a temperate-continental transitional climate and reddish-brown soil. Due to favorable weather conditions, with moderate temperatures, the green bean plants developed harmoniously and maintained an extended productive period until October 13th (12 harvestings were carried out between September 2 and October 13).

For testing, 16 green bean plants were planted and divided into 4 experimental groups, each with four plants arranged in a square (distance between plants: 50 cm and distance between rows: 50cm): 4 plants in Plot L1, treated with a biofertilizer mixture composed of 75% nettle and 25% sage; 4 plants in Plot L2, treated with a biofertilizer mixture of 50% nettle and 50% sage; 4 plants in Plot L3, treated with a biofertilizer mixture of 25% nettle and 75% sage; and 4 plants in Plot L4, which served as the control group, remaining untreated.

To prepare the solution, 300 ml of liquid mixture was used, composed of 200 ml of water and the respective amounts of nettle and sage according to the set percentages for each experimental group. Biofertilizer application on the leaves of the green bean plants was carried out over a period of 12 weeks, starting from the second week after plant emergence, for plots L1, L2, and L3. The treatment consisted of regular and even spraying of the plants in group with the biofertilizer solution once a week to effectively evaluate its impact on plant growth and development.

The diameter of the green bean pods was measured using electronic calipers, and their length was determined with a measuring tape.

RESULTS AND DISCUSSION

Table 1 presents the average values for the total polyphenol content in nettle and sage extracts, as well as their antioxidant capacity.

Table 1. Total polyphenol content and antioxidant capacity for nettle and sage extracts

	Nettle (*Urtica dioica*)	**Sage (*Salvia officinalis*)**
Total Polyphenol Content (mg GAE/100 g) (mg GAE·100 g^{-1})	7.09 ± 0.17	21.51 ± 0.38
Antioxidant Capacity (mg Trolox/100 g) (mg Trolox·100 g^{-1})	12.03 ± 0.30	72.74 ± 1.71

The total polyphenol content in the nettle extract is higher than the values reported in the study of Florez et al. (2022). According to recent research (Durovic et al., 2023; Zekovic et al., 2017; Durovic et al., 2024), the primary polyphenols extracted through ultrasound-assisted methods, such as 5-O-caffeoylquinic acid, caffeic acid, p-coumaric acid, ferulic acid, p-hydroxybenzoic acid, rutin, sinapic acid, quercetin, and kaempferol, play a crucial role in protecting plant health and integrity. These compounds contribute to plant growth and development due to their antioxidant and antimicrobial properties, essential for defense against oxidative stress and pathogens.

Additionally, the polyphenol content in sage extract is considerably higher than that reported in the study of Stanciu et al. (2019). The polyphenols in sage, including caffeic acid, rosmarinic acid, luteolin-7-glucoside, carnosic acid, carnosol, and ursolic acid, identified by Sharma et al. (2020), and Dent et al. (2015), play an essential role in the plant's direct defense against insects and pathogens, thus aiding its protection.

The concentrations of elements (mg/L) in nettle and sage extracts were identified as follows: for nettle extracts - K: 1003, P: 64.41, Mg: 40.90, and Ca: 170.1; and for sage extracts - K: 405, P: 20.96, Mg: 68.14, and Ca: 102.07. Similar to the studies (Knezevic et al., 2023; Then et al., 2004), significant concentrations of these elements were identified, which are essential for plant development, contributing to growth and nutrient absorption processes.

The chlorophyll content of plants in the four experimental plots was continuously monitored over 14 weeks (starting from the second week after plant emergence), as shown in Figure 2.

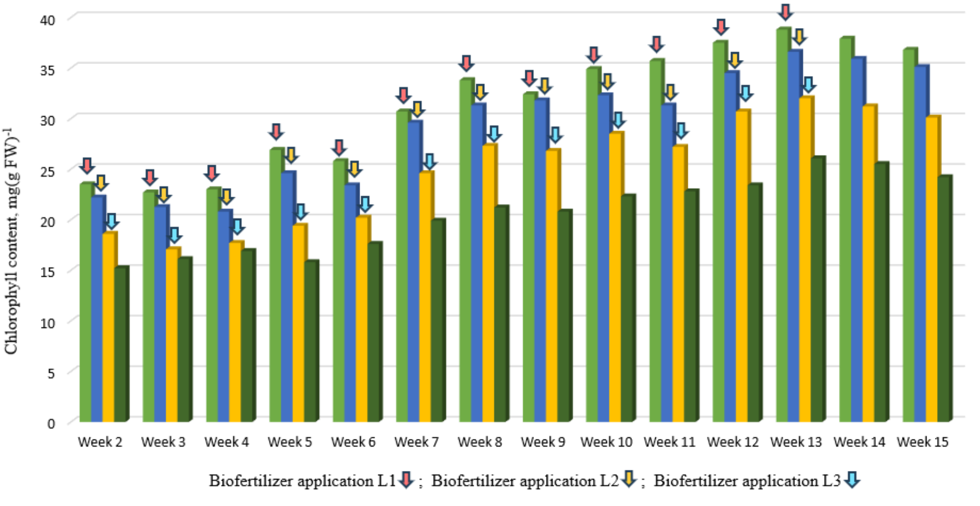

Figure 2. Monitoring of chlorophyll content in green bean plants over the 14-week period for plots L1, L2, and L3.

In the 12th week, all four experimental plots reached peak chlorophyll levels; however, L1 consistently showed the highest values compared to the other experimental plots. As shown in Figure 2, chlorophyll content begins to decline for the three plots starting from the 14th week, after foliar application of biofertilizers on green bean plants was discontinued.

Similarly, the study (Peterson and Jensen, 1986) also demonstrated a significant impact of nettle extracts on increasing chlorophyll levels in plants.

The productivity of green bean pods in the experimental plots over a 6-week harvesting period is presented in Figure 3.

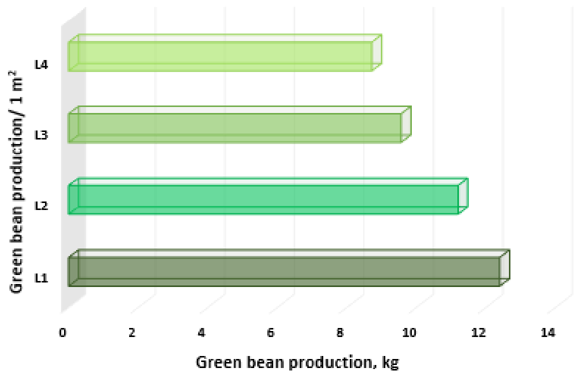

Figure 3. Green bean pod production for L1, L2, L3, and L4.

The pod production in Plot L1, approximately 42.2% higher than in Plot L4, suggests an increased efficiency of the treatment applied in L1. This increase may indicate that the biofertilizer used in L1 improves nutrient absorption or stimulates the plant's physiological processes, resulting in higher yield.

The effect of biofertilizers on the dimensional characteristics of green bean pods, particularly length and diameter, was significant, as shown in Figure 4. Pod diameter was determined by measuring the midpoint of each pod.

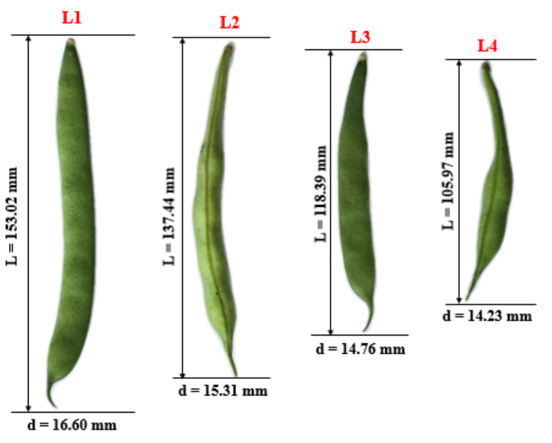

Figure 4. Green bean pod sizes for Plots: L1, L2, L3, and L4.

Based on the data in Figure 4, the most notable differences are observed in the pod sizes of green beans from Plots L1 and L4. In terms of length, the pods in L1 are approximately 10.18% longer than those in L2, 22.63% longer than those in L3, and 30.75% longer than those in L4. Similar to findings from previous studies (Maricic et al., 2022; Maricic et al., 2021), it appears that treatments with plant extracts contribute to improving the quality and characteristics of green bean pods.

The growth progression of green bean plants in the four experimental plots is shown in Figure 5. Green beans in Plot L1 had approximately 24.7% more flowers compared to L2, around 31.2% more than L3, and about 42.9% more than L4.

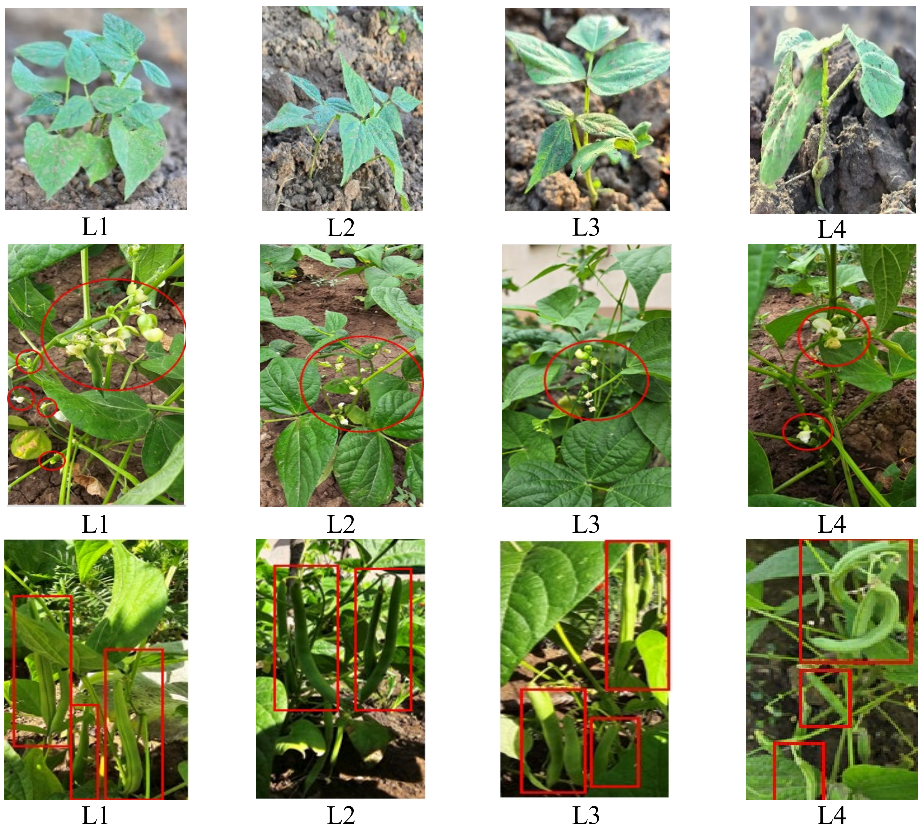

Figure 5. Growth progression of green bean plants in experimental Plots L1, L2, L3, and L4

The pods of green bean plants in Plot L4 showed reduced growth and development and were also attacked by pests, as shown in Figure 6.

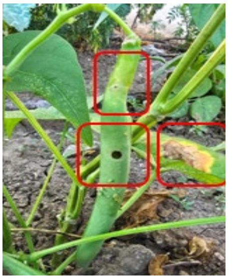

Figure 6. Green beans in Plot L4 affected by diseases and pests

The pods and leaves of green bean plants in Plot L4 exhibited visible changes, with spots appearing on the leaves (Fig. 6), most likely caused by common bean blight (*Xanthomonas campestris* pv. *phaseoli*).

CONCLUSIONS

The study on the biostimulatory effects of nettle and sage extracts on green bean development demonstrated a significant impact of foliar treatments on crop growth and productivity. The treatment applied in L1, composed of 75% nettle and 25% sage, showed the most pronounced biostimulatory effect, resulting in consistently high chlorophyll content throughout the monitoring period (approximately 53% higher than in L4) and maximum pod production (about 42.2% higher than in L4). These results suggest that a high concentration of nettle extract effectively stimulates metabolic processes and photosynthesis, while sage extract contributes to the protection against pests and diseases. The findings also highlight a synergistic effect between nettle and sage; however, as the proportion of sage increases (in L2 and L3 treatments), the biostimulatory effects diminishes. Untreated plants (L4) showed the lowest performance in terms of both chlorophyll content and pod production, underscoring the necessity of foliar treatments to optimize growth and crop productivity.

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GRAIN DRYING EFFICIENCY AND POTENTIAL OF POSTHARVEST BIOMASS RESIDUES FOR BIOGAS PRODUCTION

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ABSTRACT

Each type of grain requires specific processing due to its natural moisture content, which must be reduced by drying as one of the most important processes carried out prior to their storage and subsequent use. This process is particularly important for agricultural crops such as rapeseed (Brassica napus), oats (Avena sativa) and field peas (Pisum sativum L.), which are widely used in the food industry and as animal feed and are the focus of this research. The choice of an effective drying process is crucial to preserve the important physical and chemical properties of the grain. Laboratory research investigated advanced drying methods, fluidized bed drying and vacuum drying, allowing precise control of temperature and drying conditions to achieve a specific moisture content of the grain. The chemical analyzes included the determination of the ash, coke, fat, starch and protein content of the grain as well as the elemental composition. At the end of the research, an analysis of the lignocellulosic composition of the post-harvest residues of the aforementioned plants was carried out to determine whether they could be used as a raw material for the production of biofuels such as biogas.

Keywords: *grain, drying, animal feed, biomass, biogas*

INTRODUCTION

Ensuring a quality food supply is critical not only for a growing population, but also to feed the increasing number of pets and livestock that contribute to global food systems. With increasing demand for meat, milk, eggs and other animal products due to population growth

- there are currently just over 8 billion people on the planet - and changing diets, intensification of agricultural production is essential. However, this must be balanced with maintaining a high nutritional value of animal feed, as the quality of feed has a direct impact on animal health, productivity and the quality of animal products. Achieving this balance is critical to sustainably meeting global demand (Castro et al., 2023). Maximizing productivity in animal food production depends on providing animals with nutrient-rich feed that promotes growth and health. Unfortunately, improperly processed feed often lacks essential nutrients, reducing production and compromising the quality of meat, milk and eggs. This affects farm profitability and animal health, leading to greater susceptibility to disease, a higher resource burden and higher operating costs (Baris, 2023).

These problems affect the entire food chain and compromise the sustainability and efficiency of food production systems. Consequently, research to improve the quality and nutritional value of animal feed has become essential. By using modern technologies and advanced processing techniques such as extrusion and pelleting, nutrient encapsulation and fermentation and biotechnological additives, producers can develop more effective feed formulations that preserve nutrients, improve digestibility and promote healthier and more productive livestock (Garba and Fırıncıoğlu, 2023). This approach increases farm productivity and supports a more reliable and sustainable food supply chain (Michel et al., 2024). A crucial step in maintaining the nutritional quality of feed, particularly crops such as oats, rapeseed, and field peas, is the use of modern drying processes such as infrared or microwave drying, that preserve important nutrients (Liu et al., 2021). Conventional drying often fails to preserve sensitive vitamins, proteins and enzymes (Chobot et al., 2024).

This underlines the need for innovative drying technologies that optimize the process without compromising nutritional value. Techniques such as fluidized bed drying, vacuum drying and other advanced processes offer controlled environments, precise temperature management and reduced nutrient loss. These technologies not only help to preserve important nutrients, but also improve the overall quality and shelf life of agricultural products, increase the nutritional value of animal feed and support sustainable food production (Indiarto et al., 2021). Modern drying technologies offer farmers and food processors new opportunities to improve product quality and shelf life while preserving important nutrients. However, it is important to thoroughly investigate the impact of these technologies on the chemical properties and nutritional value of different crops to better understand their effectiveness and potential benefits (Lamidi et al., 2019).

The aim of this study was to investigate the physical and chemical properties of oats, rapeseed and field peas and to analyse the effects of fluidized bed and vacuum drying on the quality of these crops for animal feed production, as well as to evaluate whether the post-harvest residues of said crops can be used for biogas production, which offers a sustainable way of converting agricultural waste into renewable energy while reducing the environmental impact. The main focus was to determine the best drying method that preserves the nutritional value, using different drying temperatures (50, 60 and 70 °C) until equilibrium moisture content was reached. Chemical analyses were used to determine the moisture, ash, coke, fat, starch and protein content as well as lignocellulosic composition. The results will help to select the most efficient drying method to preserve the nutritional value and thus improve the quality of the animal feed.

MATERIALS AND METHODS

Three types of crops were examined in the study: rapeseed (*Brassica napus*), oats (*Avena sativa*) and field pea (*Pisum sativum* L.). The study was conducted at the Faculty of Agriculture of the University of Zagreb in the Laboratory for Sustainable Technologies and Renewable Energy Sources. The moisture content was measured using a Memmert UF160 laboratory dryer (Memmert GmbH + Co. KG, Schwabach, 2021, Germany) in accordance with the HRN EN ISO 18134-2:2024 standard, while the ash content (HRN EN ISO 18122:2022) and coke content (HRN EN ISO 18123:2015) were determined using a Nabertherm L9/11/B170 muffle furnace (Nabertherm GmbH, Lilienthal, 2008, Germany). As the moisture content of the samples fluctuated, they were rehydrated to bring them to an average moisture content corresponding to that usual at harvest. This was done by adding a certain amount of distilled water directly to the grain according to the guidelines of the National Institute of Standardisation and Metrology. The rehydration was carried out according to a special calculation:

$$W = [(W_1 - W_2) / (100 - W_2)] \times M_1 \ (\%) \quad (1)$$

where: W = amount of distilled water needed (ml) or (g), W_1 = initial moisture content of the sample (%), W_2 = target moisture content (%), M_1 = mass of the sample to be rehydrated (g).

The fluidized bed drying was carried out with the Retsch TG 200 fluidized bed dryer (Retsch GmbH, Haan, 2021, Germany), which was designed for use in quality control, sample preparation and research and development. It enables gentle drying of organic, inorganic, chemical or pharmaceutical bulk materials without local overheating. Vacuum drying was carried out using the Memmert VO101 vacuum dryer (Memmert GmbH + Co. KG, Schwabach, 2021, Germany), which is suitable for a wide range of applications, including drying and heating of materials. The starch content was determined using the polarimetric method according to the HRN ISO 6493:2001 standard with a Kruss P3001 polarimeter (A. Krüss Optronic GmbH, 2003, Hamburg, Germany) and the following calculation:

$$\text{Starch} = 100 \times \alpha \times 100 / (\alpha)^{20}D \times L \times m \ (\%) \quad (2)$$

where: α — observed rotation angle, $(\alpha)^{20}D$ — specific rotation angle of starch, L — length of polarization tube, m — sample mass (g).

The fat content was determined using the Soxhlet R108S BEHRotest extractor (Labor-Technik-GmbH, Düsseldorf, 2021, Germany) according to the HRN EN 6492:2001 method and the following calculation:

$$\text{Fat} = [(m_1 - m_0) / m_s] \times 100 \ (\%) \quad (3)$$

where: m_1 = mass of the container after extraction (g), m_0 = mass of the container before extraction (g), m_s = mass of the sample in the thimble (g)

The elemental composition (carbon, hydrogen, nitrogen and sulfur) was determined using the dry combustion method in the Vario Macro CHNS analyzer (Elementar Analysensysteme GmbH, 2009, Germany) according to the protocols for the determination of carbon, hydrogen and nitrogen (HRN EN ISO 16948:2015) and sulfur (HRN EN ISO 16994:2016). The oxygen content was calculated on the basis of the difference. The analysis of the lignocellulose composition was carried out according to standard methods (TAPPI) and on the basis of previous studies (Antonović et al., 2019; Matin et al., 2024).

RESULTS AND DISCUSSION

The application of the above analyses and relevant methods has led to the following main results, which provide valuable insights and contribute to a deeper understanding of the subject. Moisture content was measured in samples of oats, rapeseed, and field pea both before and after rehydration (Table 1). The ash, coke, starch, fat and protein content was measured in the initial samples before drying began.

Table 1. Chemical composition of the initial samples (%)

Sample	Initial moisture	Moisture after rehydration	Ash	Coke	Starch	Fat	Proteins
Oats	10.30	20.40	3.50	20.47	32.45	6.73	9.89
Rapeseed	8.10	20.30	3.87	10.48	46.03	28.56	12.43
Field pea	11.80	16.50	3.54	17.87	29.40	0.96	21.89

The moisture content of the tested samples is almost identical to the literature, as Nao et al. (2018) report values between 11.8 and 27.0% for oats, Izli et al. (2009) from 8.3 to 27.4% for rapeseed and Miller et al. (2019) from 10.6 to 13.3% for field peas. After drying the samples (50, 60 and 70 °C) in a fluidized bed and under vacuum, the ash and coke content was analysed again (Table 2). The ash content decreased in oats and increased in rapeseed, while in field peas a lower drying temperature led to a lower ash content after drying in the fluidized bed. Vacuum drying had the greatest effect on increasing the ash content in rapeseed, while the ash content of oats and field peas remained almost the same or decreased slightly.

Table 2. Ash and coke content after drying (%)

	Temperature (°C)	Ash		Coke	
		Fluid	Vacuum	Fluid	Vacuum
Oats	50	2.94	3.23	19.69	20.14
	60	3.20	3.25	19.84	19.73
	70	3.21	3.50	16.52	20.63
Rapeseed	50	3.90	4.00	11.99	11.99
	60	3.96	4.15	11.87	11.39
	70	3.97	4.16	11.98	11.86
Field pea	50	3.24	3.44	17.25	16.53
	60	3.35	3.48	17.40	17.44
	70	3.50	3.52	16.72	16.49

The ash content of oats is consistent with the literature, as Sangwan et al. (2014) report values between 2.7 and 3.5%, just as Millar et al. (2019) report values between 2.76 and 3.5% for field peas. For rapeseed, the ash content was slightly lower than the 4.84% reported by Gagour et al. (2022). Fluidized bed drying of oats and field peas led to a decrease in coke content, while it led to an increase in rapeseed. During vacuum drying, the coke content of oats and field peas decreased slightly, while it increased in rapeseed. A comparison with the literature shows that the coke content in oats is consistent, as Kovačević (2018) states 21.1%, while in rapeseed it is lower than the 13.18% reported by Matin et al. (2021).

After fluidized bed drying, the starch and fat content of oats remained nearly unchanged, while protein slightly decreased. In rapeseed, proportions stayed similar, and in field peas, starch and protein content increased, while fat remained unchanged. During vacuum drying, oats saw an increase in starch, with fat and protein remaining the same. In rapeseed, starch and protein remained stable, but fat increased slightly. For field peas, starch rose from 29% to 37%, with no significant change in fat or protein content (Table 3).

Table 3. Starch, fat and protein content after drying (%)

	Temperature (°C)	**Starch**		**Fat**		**Protein**	
		Fluid	Vacuum	Fluid	Vacuum	Fluid	Vacuum
Oats	50	33.63	38.56	6.58	6.62	8.89	9.83
	60	31.83	38.10	7.53	7.60	8.66	9.65
	70	29.04	38.06	6.13	6.21	8.46	9.52
Rapeseed	50	46.84	46.85	29.87	30.13	12.02	12.21
	60	44.48	46.48	30.26	30.26	11.83	11.92
	70	43.52	46.08	29.23	29.31	11.66	11.52
Field pea	50	24.44	36.69	1.03	0.95	20.15	21.58
	60	26.23	35.67	1.07	1.06	18.82	21.39
	70	26.58	37.32	0.98	0.85	18.77	21.25

In the literature, Doehlert et al. (2013) report a starch content of between 51.0 and 65.0% for oats, Mäkinen et al. (2017) a protein content of between 12.0 and 17.0% and Sterna et al. (2016) a fat content of between 4.9 and 10.5%. For rapeseed, Gagour et al. (2022) state a protein content of 20.85%, Straková et al. (2008) a starch content between 32.5 and 40.4% and Stepien et al. (2017) a fat content between 46.0 and 49.1%. Millar et al. (2019) state a protein content of between 21.0 and 22.0% for field peas, while García Arteaga et al. (2021) state a starch content of between 32.5 and 56.2% and a fat content of between 1.9 and 2.5%.

The elemental composition of key elements such as carbon (C), hydrogen (H), oxygen (O), nitrogen (N) and sulfur (S) is crucial for assessing nutritional and energy value, particularly in food science, commodity production and biofuel processing. Tables 4 and 5 show the elemental composition of the original and dried samples, with no significant differences found between them.

Table 4. Elemental composition of the initial samples (%)

Sample	N	C	S	H	O
Oats	1.58	47.14	0.05	6.09	45.14
Rapeseed	1.99	45.34	0.05	5.99	46.63
Field pea	3.50	41.33	0.04	6.25	48.87

Table 5. Elemental composition of the samples after drying (%)

Sample	T (°C)	Fluid					Vacuum				
		N	C	S	H	O	N	C	S	H	O
Oats	50	1.42	46.23	0.05	5.99	46.31	1.57	46.94	0.05	6.02	45.41
	60	1.36	46.03	0.04	5.85	46.69	1.54	46.68	0.04	6.01	45.73
	70	1.35	45.96	0.04	5.84	46.80	1.52	46.55	0.04	5.99	45.90
Rapeseed	50	1.92	44.84	0.04	5.63	47.57	1.95	45.01	0.04	5.92	47.07
	60	1.89	44.06	0.04	5.61	48.40	1.91	44.88	0.04	5.90	47.27
	70	1.87	43.98	0.03	5.59	48.53	1.84	44.55	0.04	5.89	47.67
Field pea	50	3.22	40.87	0.04	6.19	49.68	3.45	41.05	0.04	6.24	49.22
	60	3.01	39.88	0.04	6.12	50.95	3.42	40.87	0.04	6.21	49.47
	70	3.00	39.78	0.04	6.10	51.08	3.40	40.33	0.03	6.20	50.04

In the literature, Kovačević (2018) gives the following element composition for oats: 40.67% carbon, 5.95% hydrogen, 51.47% oxygen, 1.55% nitrogen and 0.36% sulfur. For rapeseed, Matin et al. (2021) report 44.38% carbon, 6.38% hydrogen, 48.22% oxygen and 0.26% sulfur. A comparison of the values for field peas was not possible due to a lack of available literature.

The lignocellulosic composition is crucial for biofuels production as it is a rich source of complex carbohydrates such as cellulose, hemicellulose and lignin, which can be broken down by microorganisms to produce methane. A high content of lignocellulose in biomass increases the yield and efficiency of biogas production, making it a valuable component of renewable energy production. Table 6 shows the lignocellulosic composition of the agricultural crops studied.

Table 6. Lignocellulosic composition of the initial samples (%)

Sample	Cellulose	Lignin	Hemicellulose
Oats	33.89	12.97	27.44
Rapeseed	43.21	16.11	22.76
Field pea	31.54	17.05	23.19

In the literature on oat straw, Rencoret et al. (2023) report a cellulose content of 26.4 to 34.6%, a lignin content of 11.0 to 13.4% and a hemicellulose content of 25.2 to 28.3%, while

Isikgor and Becer (2015) report 31.0 to 35.0% cellulose, 10.0 to 15.0% lignin and 20.0 to 26.0% hemicellulose. For rapeseed stalks, Rozenfelde et al. (2021) state a cellulose content of between 40.0 and 46.0%, a lignin content of between 17.0 and 21.0% and a hemicellulose content of between 22.0 and 23.0%. Sathish et al. (2024) report 33.0% cellulose, 18.0% lignin and 24.0% hemicellulose for field pea stalks. For corn, the crop most commonly used for biogas production, Zhang et al. (2021) report 36.89% cellulose, 17.38% lignin and 20.42% hemicellulose, while Khan et al. (2024) assume 40.8 to 42.2% cellulose, 7.47 to 8.80% lignin and 25.6 to 26.8% hemicellulose.

CONCLUSIONS

Both fluidized bed and vacuum drying have different effects on the ash, coke, starch, protein and fat content of oats, rapeseed and field peas. Fluidized bed drying generally led to a reduction in the ash and coke content of oats and field peas, while this increased in rapeseed. Conversely, vacuum drying caused the most significant increase in ash content for rapeseed while oats and field peas remained relatively unchanged or were slightly reduced. Nutrient composition also varied, with fluidized bed drying decreasing protein content in oats and increasing starch and protein in field peas, while vacuum drying maintained or slightly increased starch in oats and rapeseed and resulted in a notable increase in starch in field peas.

The drying processes had only a minimal effect on the elemental composition (carbon, hydrogen, nitrogen, sulfur and oxygen) of all samples. This stability of elemental composition suggests that both drying processes effectively preserve primary biochemical properties, supporting their applicability in scenarios where nutrient integrity is important. These results emphasize the suitability of these drying methods for preserving nutritional value in applications requiring high-quality, dried agricultural products.

In addition, the results show that oat, rapeseed and field pea biomass are suitable for biogas production due to their lignocellulosic composition, which provides fermentable substances for methane formation. Oat straw has a balanced cellulose and hemicellulose content that can be easily digested by anaerobic bacteria and has a moderate lignin content that does not hinder digestion. Rapeseed stalks, which are often used for biogas production due to their high biomass yield, have a high cellulose content and can yield a considerable amount of biogas, although a slightly higher lignin content can slow down degradation without preventing biogas production. Pea stems are similar to oats, with slightly less cellulose than rapeseed, sufficient hemicellulose and a lignin content suitable for effective biogas production.

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50. ACTUAL TASKS ON AGRICULTURAL ENGINEERING

Original scientific paper

MATHEMATICAL MODEL FOR THE PROCESS OF COMPACTING BIOMASS GRANULAR MATERIALS

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ABSTRACT

This study presents a mathematical model for compacting biomass granular materials, offering a refined explanation of the compaction process. By leveraging continuum mechanics, the model formulates a system of partial differential equations, enabling the analysis of displacement, velocity, strain, stress, and density fields within the biomass during compaction. The model aids in predicting the time required to achieve a target density under set conditions and provides insights into constitutive behaviour essential for designing durable biomass pellets. Experimental validation using sawdust confirms the model's capability to replicate real-world compression dynamics. Results indicate the model's effectiveness in simulating density and deformation profiles, offering a predictive framework for optimizing compaction processes. This approach holds promise for advancing the understanding of biomass compaction and supporting future efforts in pellet durability and performance optimization.

Keywords: *granular materials, compression, continuous mechanics, mathematical model*

INTRODUCTION

Compaction processes of granular materials up to transformation into solid bodies are physical processes that are difficult to model theoretically because it can be stated that these are processes that include a physical transformation of the aggregation state.

Powder (granular) materials are a solid material that comes in the form of fine particles, belonging to the category of granular materials. Granular (or granulated) materials are a lot of solid particles, large enough that they are not subject to thermal fluctuations or movements (Stover et al., 2023; Ge, 1994). The lower limit of the size of these particles is about 1 μm, below which the particles would have colloidal characteristics. Among the easily measurable characteristics of powders, researchers (Guo et al., 2012; Denny, 2002; Huang, 1982) mention: density, humidity and slip angle. The factors that influence the behaviour of powders are: particle size distribution, particle shape, particle surface roughness, chemical characteristics, mechanical characteristics (elasticity, plasticity, viscosity) (Suhag et al., 2024). External factors that influence the behaviour of powders are: humidity, environment temperature and pressure, as well as storage time (Umang et al., 2017, Panelli & Filho, 2001). The characteristics of the environment have a great influence on the fluidity or the flow capacity of the powder under the action of an external force (the influence being very high when the material does not require much energy to flow) (Suhag et al., 2024). The fluid or solid behaviour of powders and a measure of the approximation of the material as belonging of the solids or fluids category is considered the compressibility index. A high value of the compressibility index means a state close to the solid state, and a small value of it means that a state close of the fluid state. Also, for the estimation of behaviour, the Hausner's ratio (the ratio between the density of the spun material and the initial one) can be used,. a high value indicating a solid body behaviour, while a small value implies a fluid-like behaviour for the powder (Cooper & Eaton, 1962).

Granular materials can swing between the state of fluid and solid aggregation. The transition between these states can be estimated according to the two parameters mentioned by (Zegzulka, 2003, Comoglu, 2007) and which is expressed as a ratio of volumes or densities (Rudnicki, 2006). As a consequence, the method of modelling approached will have to contain the parameters with which it is possible to calculate, possibly forecast, parameters of estimation of the state of aggregation (Jones, 1960).

Biomass powders are finely ground materials derived from organic sources, primarily plants, used as a biofuel, additive, or raw material for various industrial applications. They come from renewable sources like agricultural residues (corn stalks, wheat straw), wood waste, algae, or dedicated energy crops (such as miscanthus and switchgrass) (Gageanu et al., 2017; Ungureanu et al., 2018, Lisowski et al., 2020).

Biomass powder compaction transforms loose, low-density biomass powder into compact, solid shapes that are easier to handle, store, transport, and burn more efficiently (Adapa et al., 2009; Gageanu et al., 2021; Voicea et al., 2015).

The paper presents a validated mathematical model for the process of compacting biomass powder materials, but not limited to this type of powder.

MATERIALS AND METHODS

In order to develop the model, the following notations and names shown in Table 1 were used, in accordance with literature (Lazar., 19833; Soos & Teodosiu, 1983; Iesan, 1979; Rudnicki, 2006; Abeyaratne, 2015).

The modelling method approached for this model uses the concept of continuous body. Using this notion, the physical bodies received a mathematical model, relatively easy to manipulate and interpret. Using the mathematical model of continuous bodies, in the last two hundred years, (Cauchy, 1827), the loading processes for solid, fluid and other materials have been successfully modelled. Separately, these types of bodies have been subject to Solid Mechanics and Fluid Mechanics.

Table 1. Notations and names used to define the compression model

Name	Notation	Units
Position of the generic particle in the initial configuration	x	m
Position of the generic particle in the actual configuration	X	m
Time	t	s
Motion function, Deformation function	χ	m
The velocity	v	m/s
The acceleration	a	m/s^2
Acceleration of the environmental field (usually gravitational)	b	m/s^2
Body density field in the initial configuration	ρ_0	kg/m^3
Body density field in the current configuration	ρ	kg/m^3
Deformation Gradient	F	-
Displacement field	u	m
Strain field	ε	-
Stress field	σ	Pa
Variation of the displacement speed of the compression piston	Ω	m/s
Compressibility Index	IC	-
Hausner ratio	H	-
The cross-sectional area of the cylindrical mould	S	m^2
Parameter of the constitutive equation (11)	A	Pa
Parameter of the constitutive equation (11)	ε_s	-
The diameter of the mould	ϕ	m

The essence of the behavioural difference of the two categories of continuous bodies is given by the constitutive equations. The separation between the solid and fluid materials is difficult to quantify, because, depending on the nature and intensity of the charges (mechanical, thermal, electromagnetic, radiation, gravitational, etc.) they may behave in one way or another. For this reason, the model is interesting because it deals with a mechanical transformation that transforms a material with dual solid-flow behaviour, into a solid material (at least at the end of the dynamic process). An important problem of this model remains the one regarding the correctness of the modelling of the granular material through a continuous body. In order to validate this approach, complex experiments regarding granulation size and chemical composition would be needed, with the minimum volume limit at which the model makes sense: the representative elementary volume, (Hill, 1963), or the unit cell. In this paper, the issue of model validation under this aspect was not addressed.

The geometry of the model is shown in Figure 1. At time t = 0 s, the reference or initial configuration of the body is drawn (grey area inside the cylindrical section of the mould, left). An intermediate configuration in the compression process is given for some time t, in the middle. On the right is given the configuration of the body at the end of the compression process, respectively the pellets at the final time, t=T_0.

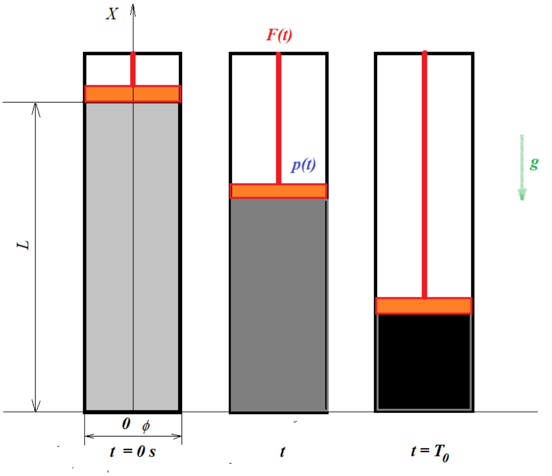

Figure 1. Principle sketch of the geometry of the mathematical model of the granular material compaction

According to the basic literature in the field of continuous mechanics, (Cristescu & Suliciu, 1976; Lazar, 1983; Soos & Teodosiu, 1983; Iesan, 1979), the deformation of a body is mathematically described by the equation:

$$x = \chi(X, t) \tag{1}$$

The velocity of the particle is defined by the relation:

$$v = \dot{x} = \frac{d}{dt}\chi(X, t) \tag{2}$$

and particle acceleration, with the help of the relation:

$$a = \ddot{x} = \frac{d^2}{dt^2}\chi(X, t) \tag{3}$$

The deformation gradient is given by the formula:

$$F = \frac{\partial\chi(X,t)}{\partial X}. \tag{4}$$

The displacement is introduced by the definition formula:

$$x = \chi(X, t) = X + u(X, t). \tag{5}$$

From (4) and (5) results:

$$F(X, t) = 1 + \frac{\partial u(X,t)}{\partial X}. \tag{6}$$

and introducing the strain[1]:

$$\varepsilon(X,t) = \frac{\partial u(X,t)}{\partial X}. \tag{7}$$

the following is obtained:

$$F(X,t) = 1 + \varepsilon(X,t). \tag{8}$$

The general equations of the mechanics of continuous environments (in Lagrangian description), written for the 1-dimensional case are:

- the *mass conservation* equation also called the *continuity equation*:

$$\rho_0 = \rho F \tag{9}$$

- *Cauchy motion law* (principle of *impulse conservation*):

$$\frac{\partial \sigma}{\partial X} + \rho_0 b = \rho_0 a \tag{10}$$

- the *constitutive equation* used to model the behaviour of a granular material such as that used in (Gageanu et al., 2019) is hyperbolic (Bell, 1984):

$$\sigma = \frac{A\varepsilon}{\varepsilon - \varepsilon_s} \tag{11}$$

Neglecting the forces generated by the mass of the granules in the gravitational field, from (10), (11) and (7), the following differential equation of the movement of the granular material column is obtained:

$$\rho_0 u_{tt} = -A\varepsilon_s \frac{u_{XX}}{(u_X - \varepsilon_S)^2}. \tag{12}$$

Because the algorithm of the Pdsolve routine of the Mathcad 15 program does not work with higher derivatives over time, equation (12) is written as a system of two differential equations with partial derivatives:

$$v_t(X,t) = -\frac{A\varepsilon_S}{\rho_0}\frac{u_{XX}(X,t)}{(u_X - \varepsilon_S)^2}, u_t(X,t)) = v(X,t). \tag{13}$$

The complete formulation of the problem of compressing the granular material in the right cylinder requires the following initial conditions:

$$u(X,0) = 0, v(X,0) = 0, \forall X \in (0,L), \tag{14}$$

[1]In this simulation test, the small deformations hypothesis, $\left|\frac{\partial u}{\partial X}\right| \ll 1$ was used.

and the next border conditions:

$$v(L,t) = \Omega(t), v(0,t) = 0, \forall t \in [0,T_0). \tag{15}$$

The displacement speed of the piston that performs the compression of the granular material, Ω, is a function of the command applied by the operator. The first condition on the border, (15) is written on a movable border of the body of granular material Problem (13), (14), (15) is solved numerically using the Pdsolve subprogram of Mathcad 15 program, the subroutine tested for analytically solvable problems, (Cardei, P., 2019).

By the modelling hypothesis, it is assumed that all the points of a cross section of the granular material column have the same vertical translation motion in any section and the friction with the die walls is neglected. The law of motion (11) was suggested by the experimental force-deformation curves, described in the experiments (Gageanu et al., 2019).

The numerical solution provides the function of displacement (deformation), u and the velocity, v. Then the functions are calculated in order: the strain, ε, using formula (7), the stress, σ, using formula (11), and finally the current density of the granular material, ρ, using continuity equation (9):

$$\rho(X,t) = \frac{\rho_0}{1+\varepsilon(X,t)}. \tag{16}$$

The volume of the pellet in formation and the initial one of the columns of uncompressed granular material, can be approximated by:

$$V_c(t) = x(0,t) \cdot S, V_0 = L \cdot S \tag{17}$$

so that the compressibility index can be calculated according to [3], by the formula:

$$IC = \frac{L - x(0,T_0)}{L} \cdot 100 \tag{18}$$

and the Hausner index:

$$H = \frac{\rho(X,T_0)}{\rho_0}. \tag{19}$$

The form of the constitutive equation (11) was thus chosen, due to the shape of the force-displacement curve of the piston, which results from the records presented in (Gageanu et al., 2019). This curve turns into a pressure - deformation curve taking into account the area of the cross section of the mould. Using this last curve, the method of the smallest squares determines the values of the parameters A and $\varepsilon_s$of the constitutive relation of the considered granular material, for the modeled experiment.

The constitutive equation of the granular material undergoes substantial changes depending on the main parameters that characterize it: humidity, ambient temperature, its granulation and distribution, the age of the material, etc. It is possible that, within a limited range of these parameters, the form of the constituent equation (11) will be preserved, only the constituent parameters become dependent on humidity, temperature and other properties of the granular material. For other, more delicate cases, another mathematical description of the experimental constitutive curve may be required. In this way (by the dependence of the constituent parameters on the parameters of the granular material), other important parameters of the granular material (physical and geometric, most likely and chemical) are involved in the numerical simulation process. The deduction of the dependence of the constitutive parameters on the physical-chemical and geometric parameters of the granular material, is considered to be a very expensive theoretical-empirical test, possibly unprofitable under the present conditions.

The constitutive law of the behaviour of the granular material, (11), is valid only from the moment the piston begins to move and until it stops at the end of the compaction process. In order to simulate the behaviour of the pellet after the completion of the formation process (when it has solid body characteristics), the constitutive law must be supplemented with new relations that return the way of unloading and relaxing, the pellet material. In the post-formation phase, the constitutive law will be substantially complicated, probably having to take into account viscous-elastic-plastic properties. The unloading law must be studied at every possible stopping point of the process, so that such a constitutive law could give indications on the durability of the pellet depending on the parameters of entry and control of the process of forming the pellet

RESULTS AND DISCUSSION

For the validation of the mathematical model, a compaction test was used from the series of tests performed and described in (Gageanu et al., 2019). The material used was sawdust with an average granulation of 0.002 m. The diameter of the straight circular cylindrical mould used in this test was ϕ = 10 mm. The bulk density of the granular material was 136.08 kg / m^3, but due to gravitational settling before the test (piston actuation), the average initial density of the granular material column reaches 161.1 kg / m^3. This redistribution of the granular material leads to an initial length of the column, and the initial column length is $L = 0.198$ m. The mass of granular material used to form the pellet has the value $m = 0.0025$ kg.

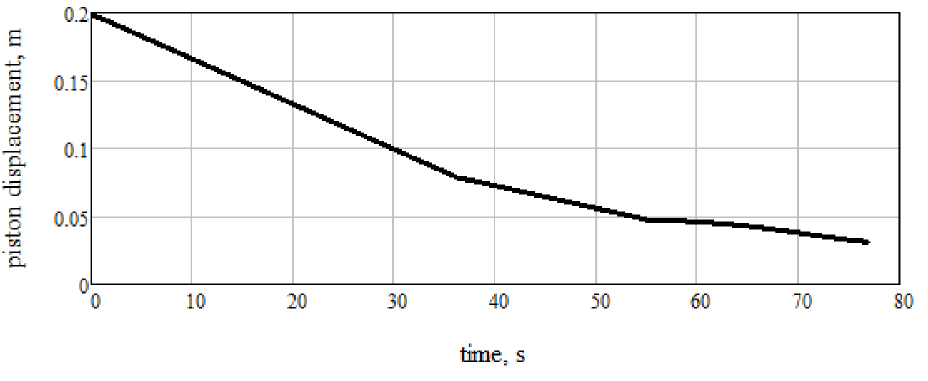

Figure 2. The displacement of the piston that compresses the granular material into the cylinder, over time.

According to the experimental records, the piston (each of its points) moved with speed having the time distribution given in figure 4. Under these conditions, the displacement of each point on the piston surface in contact with the granular material, follows the temporal law given by the curve in figure 2. As a result, the length of the granular material column at the final time of the formation process, $T_0 = 77$ s, has the value of 31.13 mm.

The density of the granular material, calculated by relating the same mass (mass conservation hypothesis) to the current volume, leads to the temporal variation of density after the curve in figure 3. The final value of the pellet density is measured, being 1021.533 kg / m^3.

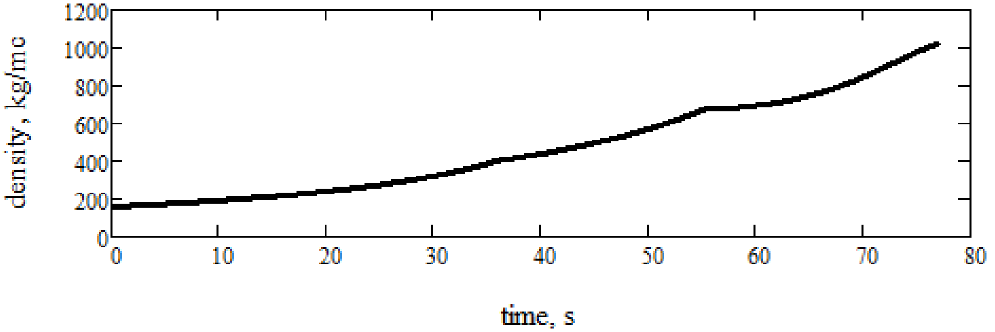

Figure 3. The variation during the compression, of the density of the granular material.

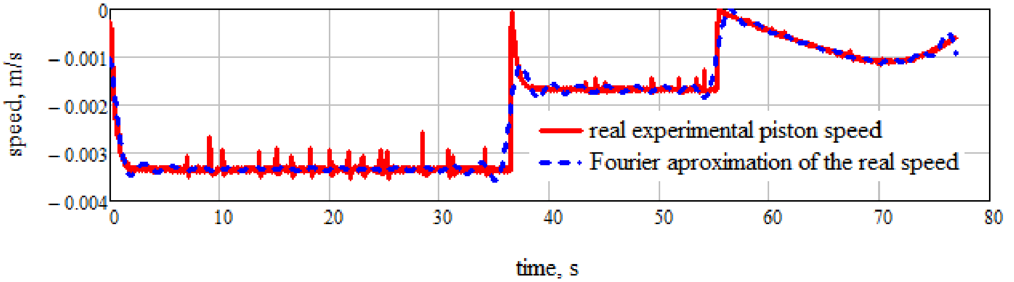

Figure 4. The time variation of the piston speed in the physical experiment and its Fourier approximation, used in numerical calculation as a boundary condition (at the boundary)

The variation of the displacement of the piston (figure 2), may give the impression of important points of change of the state of the granular material, because it is observed three linear zones united in a broken line. However, the slope shift points are most likely not related to changes in the structure of the granular material but are caused by changes in the piston speed regime, as shown by the variation of its speed in time (figure 4). The operating mode of the operator of the installation (the loading program) was not communicated to us, so the form of the variation of the loading speed cannot be commented on. Also, in figure 4 is represented graphically and the variation in time of the approximation by Fourier series for the real speed of the piston (development with 30 terms), a function that is used to control the system by the limit condition at the end driven by the compression piston, $X = L$, (15).

The variation of the compression force with the displacement of the piston (in absolute value) is graphically represented in figure 5. The variation of the pushing force of the piston depending on its displacement is easily converted to pressure by dividing the surface of the cross section of the die (figure 6).

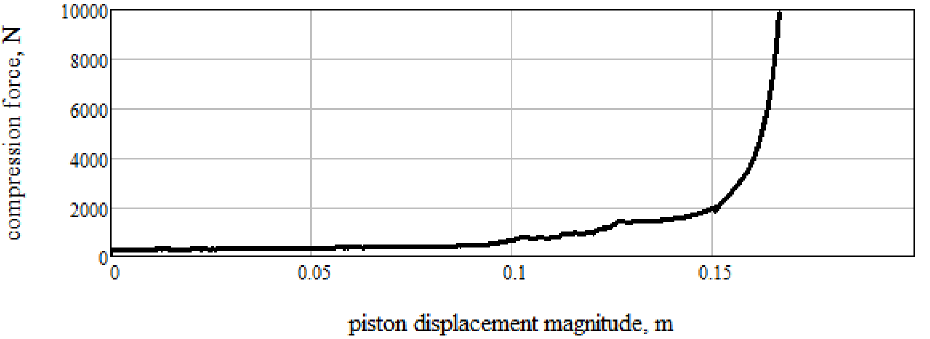

Figure 5. Dependence of the compression force of the piston on the absolute value of its displacement

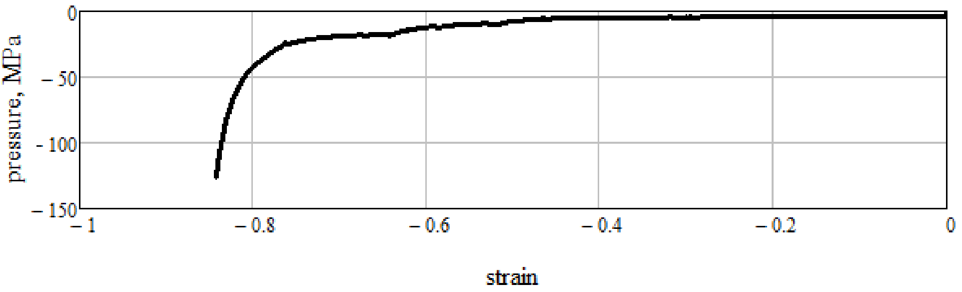

Figure 6. Dependence of the piston pressure on the strain

Figure 7 gives the form of the constitutive curve (11), inspired by the variation of pressure with the specific deformation in figure 6. From the experimental data are found: $IC = 84.23\ \%$ and $H = 6.341$. According to [15], these values indicate a very low (small) fluidity for the processed granular material).

For the solution of the problem of problem (13), (14), (15), the displacement speed of the piston obtained by Fourier series development of the real curve (figure 4) is used, to avoid sudden variations or points of discontinuity. Such points in the command function can lead to the uncontrollable amplification of the error in the numerical resolution process.

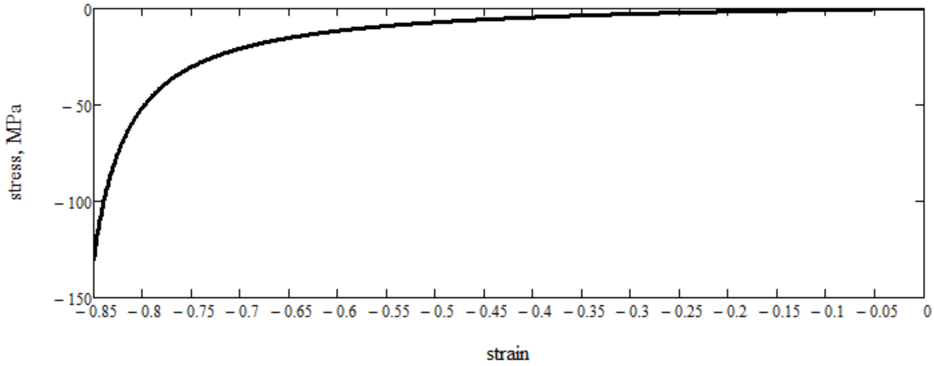

Figure 7. Stress - strain curve, deduced from the variation of the compressive force with the magnitude of the displacement

The numerical solution, for the real approximate load gives the variations of the relative displacement in time and space, as shown graphically in Figures 8 and 9. It is observed that $x(L, T_0) = 31.567$ mm (which also gives the length of the formed pellet), value very close to the one determined experimentally.

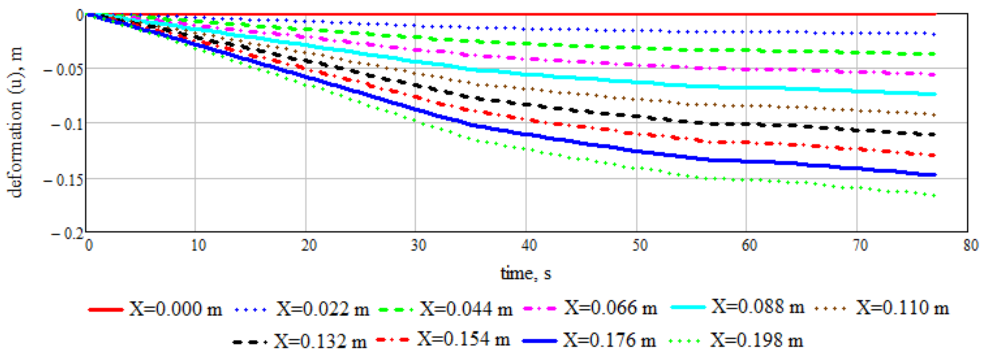

Figure 8. Dependence of the displacement, by time on 10 points of the body of granular material subjected to compression

The displacement of the central axis points of the granular material (which moves along with all the points of the respective cross section) is shown in time and space in Figures 10 and 11. It can be seen that $x(L, 0) = 0.198$ m and $x(L, 77) = 0.031567$ m. This means that the initial upper section of the column descends from 198 mm to 31.567 mm.

The proposed mathematical model effectively simulates biomass compaction but presents limitations regarding its general applicability. The model was validated using sawdust, and its extension to other biomass materials with varying moisture content, particle size, and composition requires further validation. It assumes a continuum mechanics approach, simplifying the heterogeneous behaviour of granular materials and neglecting friction effects.

Additionally, environmental factors such as humidity and temperature, which influence compaction dynamics, are not fully integrated. The model does not account for post-compaction relaxation, affecting long-term pellet stability predictions.

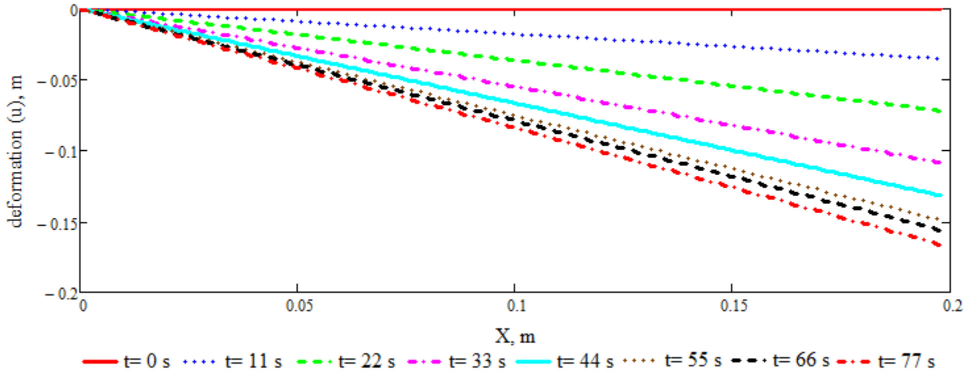

Figure 9. Dependence of the displacement of the spatial coordinate, at 8 moments of time of the material compression process

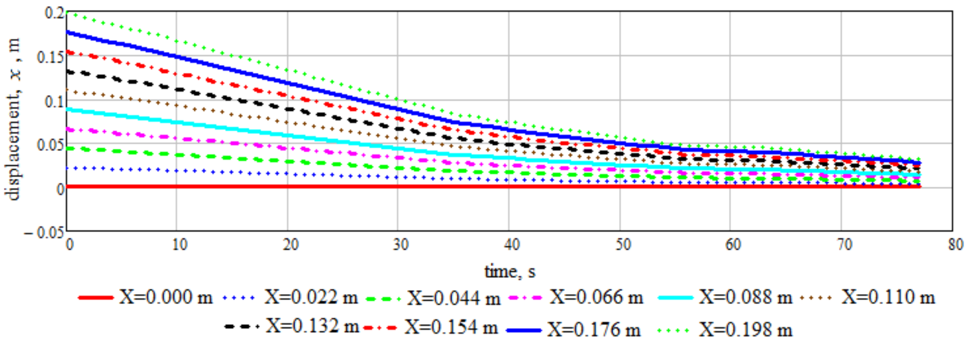

Figure 10. Dependence of the current position by the time

Despite these limitations, the model provides valuable insights for optimizing biomass compaction processes. It enables better estimation of target density, compression time, and force, aiding in the efficient design of compaction equipment. By optimizing piston velocity and compression pressure, pellet uniformity can be improved while minimizing energy consumption. The findings suggest that controlling moisture content and particle size distribution can enhance pellet durability and reduce structural defects. Additionally, manufacturers can use the model to refine die geometry and compression chamber parameters to improve pellet formation. Future work should focus on expanding model validation, incorporating multi-dimensional analyses, and refining constitutive equations to account for a broader range of biomass materials and environmental conditions.

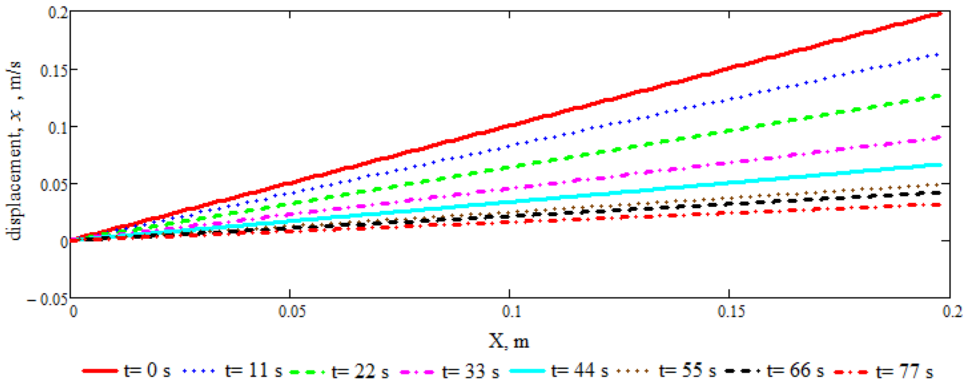

Figure 11. The distance travelled by the points of the granular material body at certain times

CONCLUSIONS

The mathematical model presented is based on the classical theory of the mechanics of continuous environments, a simple, 1-dimensional case. The model uses only characteristics of the granular material and the loading conditions of the granular material column subject to loading as data. The model represents an interesting approach because it describes (validation has shown to describe satisfactory) the transformation of a material with partial fluid characteristics into a material that, at least at the end of the compression process, has the characteristics of the solid aggregation state.

The mathematical model is capable of:

- explaining the phenomenon satisfactorily;
- giving estimates on the values of the fields of characteristic sizes inside the pellet in formation and format;
- through simulation, the model can estimate the time required to reach a certain density of pellets.

The validation of the mathematical model was achieved and shows that the modelling method has reasons to be developed to reach new objectives in describing the phenomenon of compression of granular materials. The concordance between theoretical and experimental results is more than satisfactory.

The numerical solution of the problem of mechanical request of the mathematical model is a successful test for the program used and a reason to continue using it for the higher models but also for other problems that are reduced to systems of partial derivative equations of the specified type. This test is not the first for the program used by the author testing it and for other mathematical physics problems. The results being satisfactory, this program can be used successfully, even if the efforts of understanding and testing are sometimes high.

The method of constructing the constitutive equation and the suggestion regarding the extension to other characteristics of the materials and of the process of mechanical and thermal loading, lead to an equation which gives good results in the numerical calculation. The particular form of the constitutional law does not introduce problems of convergence or precision in the calculation, at least within the limits of the calculations made for this test. For these reasons, it is recommended to try to extend the constitutive law elaborated, which can have the effect, among other things, obtaining optimal regimes of compression of granular materials.

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50. ACTUAL TASKS ON AGRICULTURAL ENGINEERING

Original scientific paper

THE INFLUENCE OF EXTERNAL FACTORS ON REFRIGERATED/FROZEN FOOD TRANSPORT

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ABSTRACT

For the transportation process it is important to predict and analyse the fuel consumption and influences of external factors on characteristics of equipment for refrigerated/frozen food transport, in conditions of controlled temperature for products, varied under different conditions. The paper proposes a hybrid method, based on small-scale modelling, for analyses the influence of external factors on the equipment for refrigerated/frozen food transport, in special conditions and different foods as: meat, product based on chocolate, frozen foods, etc. The equipment included a DAF XF 530 FT tractor pull and a SCHMITZ semitrailer with two levels charging. 50 different routes, 100 km longer, selected in Germany, on highway and national roads, in different traffic conditions: road flat or 5-8 % inclination road, sunny days and rainy days, wind at different speed, heavy or free traffic conditions, different charge weight. For each itinerary were determined average speed (in km·h^{-1}), the temperature inside the semitrailer and fuel consumption for tractor pull, respective semitrailer (refrigerator). Based on statistical analysis of the results, obvious significant differences in the average velocity distributions for the road types were determined. The mean value for freeways was the highest, and the results for the main roads and secondary roads were similar. The fuel consumption was significant different according to meteorological conditions (sun and wind), and temperature in semitrailer. For more accurate data, in the future will be necessary to eliminate the invalid and redundant data by a filtering process by pre-processing using a three-layer neural network.

***Keywords**: fuel consumption, meteorological conditions, tractor pull, small-scale modelling*

INTRODUCTION

The chain production of perishable products needs simultaneously preservation and transportation, by maintaining a proper temperature to slow biological decay processes. Such necessity affects the efficiency of the food chain and significantly increasing food waste and energy consumption (Maiorino et al., 2021). It makes refrigerated transport a critical phase of the food chain by its negative impact on energy consumption and greenhouse gas emissions due their high Global Warming Potential (GWP), as presented in (Mota-Babiloni et al., 2020). Due the importance and the key link to ensure preservation of perishable goods at adequate temperature level, the road transport refrigeration recorded a significant growth in the last few years (Fabris et al., 2024; Yang et al., 2021). International Institute of Refrigeration (IIR) informatorily note (IIR, 2021), considered approximately 40% of the total food production should be refrigerated at a certain point in their life cycle. During transport significant difficulties are encountered, particularly in warehouses, during loading and unloading operations (Mercier et al., 2017). Also, refrigerated transport systems work in a strong variability of operating conditions (weather conditions, orientation of insulated walls, frequency of loading/unloading operations), (Selvnes et al., 2021). Usually, for product refrigerated transport practiced on the road (Mercier et al, 2017) there is using special vehicles having a part of the bodywork thermally insulated equipped with systems for lowering and maintaining at a certain value the temperature inside the trailer body (Awad et al., 2020). Recent research studies (Minetto et al., 2023), reported refrigerated fleet consumes on the European road more than 3500 GWh of primary energy. In the last period a lot of models for forecasting carbon emissions from road fuel combustion were proposed (grouped in grey models (GM) (Wu et al., 2015), statistical models (Karakurt and Aydin, 2023) and non-linear models (Bota et al., 2020)). A special remark must be done to the employee's qualification level in agriculture and food industry (Tucu et al., 2021) and necessity of additional equipment to the transportation systems as forklifts, handling grippers, etc. (Tucu et al., 2010).

The objective of the present study was therefore the evaluation of the influences of external factors on characteristics of equipment for refrigerated/frozen transport, in conditions of controlled temperature for food products which are varied under different conditions.

MATERIAL AND METHODS

Equipment

The equipment included a DAF XF 530 FT tractor pull (Photo 1) and a SCHMITZ SKO 24/L - 13.4 FP 45 COOL, semitrailer with two levels charging (Photo 2) (characteristics on the producer site). A telematic system TrailerConnect®, accessed by iPhone11 were used according to DIN EN 12830.

Methodology

The paper proposes a hybrid method, based on small-scale modelling, for analyse the influence of external factors on the equipment for refrigerated/frozen food transport. Next foods were transported: meat, product based on chocolate, frozen foods, etc. As testing routes were selected 50 different routes, each on a 100 km longer, in Germany, on highway and/or national roads, in different traffic conditions (road flat or 5-8 % inclination road), sunny and rainy days, wind at different speed (0, 20, 35, 40, 60, 65 km∙h-1), heavy or free traffic conditions, different charge load (2.5 t; 8 t; 10 t; 11 t; 12 t; 16 t; 22 t).

Photo 1. DAF XF 530 FT tractor pull

Photo 2. SCHMITZ semitrailer

On each itinerary option were determined average speed (in km·h-1), the temperature inside the semitrailer and fuel consumption for tractor pull, respective semitrailer (refrigerator). The algorithm of relations between studied factors of influence and functional characteristics are presented in figure 1. Also, based on tractor pull modern facilities, a lot of other data regarding the process of transport were collected for future analysis. Based on statistical analysis of the results, obvious significant differences regarding variable distributions for the road conditions, weight and types were determined.

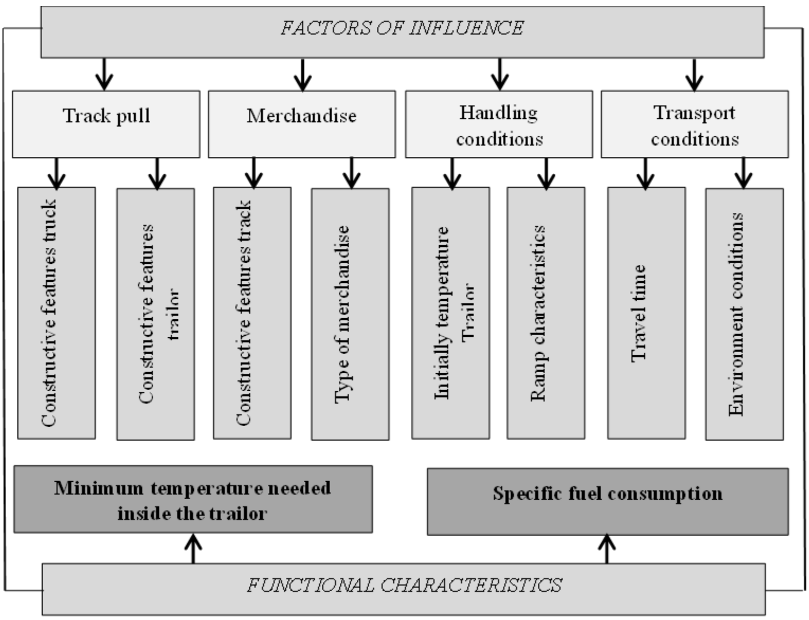

Figure 1. Relations between studied factors of influence and functional characteristics

RESULTS AND DISCUSSION

Table 1 shows one part of the determined centralized values factors and features for truck.

Table 1. Determined centralized values factors and functional features for truck

Truck itinerary	Weather conditions			Traffic conditions		Dist-ance [km]	Fuel Cons. [l/100 km]	Loads` Weight [kg]	Average Speed [km/h]	Goods	Temp. (^{0}C)
	Wind [km/h]	Sun	Rain	Heavy	Free						
IT_ 1	60				X	100	31.30	17.325	82,7	Chocolate	+15
IT_ 2	64				X	100	26.90	7.100	87,4	Chocolate	+15
IT_ 3		X		X		100	20.90	3.200	73	Meat	-18
IT_ 4		X		X		100	43.90	20.925	50	Meat	-22
IT_ 5			X	X		100	31.00	17.900	38	Meat	-20
IT_ 6		X		X		100	28.00	17.900	61,8	Meat	-20
IT_ 7			X	X		100	32.60	10.524	61,2	Pharma	+20
IT_ 8			X		X	100	27.00	17.000	83,2	Meat	+20
IT_ 9		X		X		100	27.00	13.000	77,3	Meat	-20
IT_ 10					X	100	26.00	13.300	72,9	Meat	-20
IT_ 11		X			X	100	33.00	22.000	72,2	Meat	-20
IT_ 12	39	X			X	100	31.00	22.000	82,6	Meat	-20
IT_ 13		X			X	100	35.00	22.000	83,5	Meat	-20
IT_ 14		X		X		100	44.00	22.000	72,7	Meat	-20
IT_ 15		X		X		100	40.00	22.000	77	Meat	-20
IT_ 16			X	X		100	31.00	22.300	74	Meat	-18
IT_ 17		X		X		100	31.00	22.300	79	Meat	-18
IT_ 18		X		X		100/ 5-8%	53.00	22.300	66,3	Meat	-18
IT_19			X			100	37.00	22.300	79,8	Meat	-18
IT_ 20			X	X		100	30.00	15.860	75	Meat	-20
IT_ 21			X	X		100	39.00	15.860	66,2	Meat	-20
IT_ 22		X			X	100	27.00	15.860	85,7	Meat	- 20
IT_ 23		X			X	100	24.00	14.200	85,4	Ice cream	-24
IT_ 24		X		X		100	25.00	7.820	76,3	Chocolate	+15
IT_ 25				X		100	23.00	7.820	80,4	Chocolate	+15
IT_ 26	36		X	X	-	100	27.00	16.200	78,5	Meat	-20
IT_ 27		X		X		100	34.00	16.200	60,7	Meat	-20
IT_ 28		X		X		100	34.00	16.200	73	Meat	-20

Table 1. (cont.) Determined centralized values factors and functional features for truck

Truck itinerary	Weather conditions			Traffic conditions		Dist-ance [km]	Fuel Cons. [l/100 km]	Loads` Weight [kg]	Average Speed [km/h]	Goods	Temp. (C)
	Wind [km/h]	Sun	Rain	Heavy	Free						
IT_ 29		X			X	100	28.00	16.200	84,3	Meat	-20
IT_ 30		X			X	100	26.00	16.200	82,7	Meat	-20
IT_ 31		X			X	100	24.00	11.400	87,3	Meat	-20
IT_ 32		X		X		100	32.00	16.400	77,3	Meat	-20/+2
IT_ 33		X		X		100/ 5-8%	45.00	16.400	65	Meat	-20/+2
IT_ 34		X		X		100	29.00	16.400	78,7	Meat	-20/+2
IT_ 35		X			X	100	36.00	22.000	66,3	Meat	-20
IT_36		X			X	100	29.00	22.000	89	Meat	-20
IT_ 37		X			X	100	28.00	12.745	70,7	Marzipan	+15
IT_ 38		X		X		100	25.00	8.010	73	Meat	+2
IT_ 39		X		X		100	27.00	8.010	79,6	Meat	+2
IT_ 40		X		X		100	26.00	8.010	70,4	Meat	+2
IT_ 41		X			X	100	28.00	8.010	83 ,4	Meat	+2
IT_ 42		X			X	100	24.00	2.450	83,3	Meat/Hygienic Pkg	+2
IT_ 43		X		X		100	20.00	2.450	77,2	Meat/Hygienic Pkg	+2
IT_ 44		X			X	100	20.00	2.450	82,8	Meat/Hygienic Pkg	+2
IT_ 45	20	X		X		100	32.00	22.000	67	Meat	-18
IT_ 46		X		X		100	42.00	22.000	58,4	Meat	-18
IT_ 47	35	X		X		100	33.00	12.353	61,2	Pizza	-24
IT_ 48					X	100	27.00	15.820	89,4	Meat	-20
IT_ 49				X		100	40.00	15.820	73,3	Meat	-20
IT_ 50		X			X	100	29.00	15.820	84,8	Meat	-20

After Multiple sample comparison, significant differences in the average velocity distributions for the road types were determined: the mean value for freeways was the highest, and the results for the main roads and secondary roads were similar. Also, the fuel consumption was significant different according to meteorological conditions (sun and wind), and temperature in semitrailer.

Based on information from table 1, using STATGRAPHICS Centurion, a multiple linear regression was applied considering the hypothesis of existence of one relationship between fuel consumption and three independent variables: load, average speed and temperature inside the semitrailer. The general report is presented in table 2 and ANOVA results in table 3. The output of multiple linear regression shows there is a model to describe the relationship between Fuel consumption and 3 independent variables.

Table 2 Results of general statistical analysis

Parameter	Estimate	Standard Error	T Statistic	P-Value
Average Speed	0.189181	0.0295683	6.39811	<0.001
Weight	0.00106964	0.000137465	7.78115	<0.001

Table 3 ANOVA results for mathematical model

Source	Sum of Squares	Df	Mean Square	F-Ratio	P-Value
Model	47938.6	2	23969.3	571.72	<0.001
Residual	2012.38	48	41.9246		
Total	49951.0	50			

Since the P-value in the ANOVA table is less than 0.05, there is a statistically significant relationship between the variables at the 95.0% confidence level. Also, the correlation coefficient R-squared = 95.9713 percent, R-squared (adjusted for d.f.) = 95.8874 percent, Standard Error of Est. = 6.47492, Mean absolute error = 5.21925 and results for Durbin-Watson statistic = 2.15315.

The equation of the fitted model is:

$$Fuel\ consumption = 0.189181*Average\ Speed + 0.00106964*Weight \quad (1)$$

Where:
- Average Speed, [km h^{-1}]
- Weight, [kg].

The value of R-Squared statistic indicates that the model as fitted explains 95.9713% of the variability in Fuel consumption. The adjusted R-squared statistic, which is more suitable for comparing models with different numbers of independent variables, is 95.8874%. (Note: since the model does not contain a constant, must be careful in interpreting the R-Squared values. Such R-Squared values must not be compared with those of models which do contain a constant). The standard error of the estimate values shows the standard deviation of the residuals 6.47492.

The highest P-value on the independent variables is <0.001, belonging to Average Speed. As statistics confirmed the influence of temperature on fuel consumption, but the factor has not an influence associated to speed and load of the equipment (table 2), instead other factors, as mentioned in introduction (Mercier et al., 2017), also decision process and time management. For more accurate data, in the future will be necessary to eliminate the invalid and redundant data by a filtering process by pre-processing using a three-layer neural network. The model can be improved based on a lifecycle perspective and several measures: reduce unloaded activities, optimize temperature differences between outside and inside containers and adequate procedures through better standardized operation. (Wu et al., 2022).

CONCLUSIONS

Refrigerated/frozen transport trucks' use contributes the most to climate change impacts, also in optimization of food and beverage logistics (followed by the production, recycling, and transport stages). A useful hybrid model was identified and is useful for be applied for forecasting carbon emissions from road special transport as opportunity to optimize the transport (technical and economical), and to reduce GHG emissions. The proposed relation can be useful for forecasting carbon emissions from road fuel combustion on refrigerated/frozen food transport.

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MULTI-CROP BIOMASS UTILIZATION FOR BIOENERGY PURPOSES AND EVALUATION OF PRESSED BIOFUEL PROPERTIES

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ABSTRACT

The goal of most bioenergy producers is to grow as much crop biomass as possible in the shortest possible time. However, according to the requirements of the Green Course in 2023-2027 during the period, the consumption of fertilizers and plant protection products will have to be significantly reduced. In order to fulfil all the necessary conditions for biomass production, a stationary field experiment was conducted in 2020-2022 at the Experiment Station of Vytautas Magnus University. Multi-cropped multifunctional continuously grew cultivations of maize, technical hemp and faba bean has been investigated as seven treatments: 1) Maize single-crop; 2) Hemp single-crop; 3) Faba bean single-crop; 4) Maize and hemp binary-crop; 5) Maize and faba bean binary-crop; 6) Hemp and faba bean binary-crop; 7) Maize, hemp and faba bean ternary-crop. Results of researchers of VMU AA Agronomy faculty showed, that inter-cropping is the right effective method to shortly continuously cultivate crops for energy purposes without significant negative impact on the environment and the soil properties. Presented article focuses on the evaluation of the suitability of investigated plants, that can be grown individually and as multi-crop plants, and their biomass can be produced and used for energy conversion. There were analyzed and investigated the most popular method – production of pressed solid biofuels and their burning. After harvesting the 2022 plants they were chopped and milled, and later pressed into the cylindrical 6 mm diameter pellets, which were produced using of a low power granulator (120–150 kg h^{-1}). After chopped plant milling, it was determined the fractional composition of the mill in all four samples: 55–70% of mill particle size was less than 2.0 mm. After analysis of pellet biometrical properties, was measured pellet length (it ranged from 22.6 to 25.2 mm) and the diameter of pellets, which was sufficiently stable and varied from 6.1 to 6.2 *mm. After evaluating the compressive strength of the pellets, it was found that all types of pellets were sufficiently strong, and their dry mass density reached 1040–1150 kg m^{-3}. Determined lower calorific value of pellets varied from 16.8 to 18.1 MJ kg^{-1}. Harmful gas emissions during burning of investigated pellets were sufficiently low and did not exceeded the allowed values. Finally, it can be stated, that all investigated biofuel pellets meet the most important requirements for the quality of biofuel and it can be prepared and used for burning in special boilers.*

Keywords: *multi-crop plants, maize, fiber hemp, field beans, solid biofuel, pellets, properties*

INTRODUCTION

Solid biofuels are the simplest and oldest type of biofuel. Conversion processes help remove moisture, increase energy density, improve hydrophobicity and fineness, and facilitate storage and transportation. Solid biofuels are relatively more stable, easier to handle and store. Densified products, such as fuel pellets, can be used in both domestic and industrial combustion plants (Lim et al., 2023).

Biomass is considered an environmentally friendly energy source because it serves as a carbon dioxide reduction and is a desirable alternative to fossil fuels to reduce greenhouse gas (GHG) emissions (Wang et al., 2020).

The contribution of bioenergy to the global energy matrix is expected to be 64-313 EJ (7.5–37.0%) by 2050. The composition of bioenergy supply is also projected to change significantly, with a shift from today's dominant use of fuelwood to energy crops and biodegradable waste (Errera et al., 2023).

The range of biomass raw materials from which pellet fuel can be produced is very wide, both herbaceous plants and woody species are suitable for this. The quality of the final product is influenced by various factors, both the parameters of the pelleting process and the properties of the biomass (Wei et al., 2024).

Many studies indicate that wood pellets are of better quality than pellets made from herbaceous plants, especially in terms of their bulk density, ash content, calorific value, and chemical composition. However, pellets made from herbaceous plants are an interesting way to utilize agricultural waste, mainly for industrial use. Mixing different raw materials and using binders can help improve the quality of pellets, but their use must be assessed on a case-by-case basis (Picchio et al., 2020).

Lignin, cellulose, hemicellulose, protein, lipid and moisture in biomass feedstock are the main chemical components that affect pelletization (Cui et al., 2021). It is important to select biomass with appropriate chemical composition for pelletization. The calorific value of biomass is mainly related to the lignin content, as well as the cellulose and hemicellulose content. Selecting feedstocks with high lignin content can improve the calorific value of pellets (Wei et al., 2024).

A study made by Romaneckas et al. (2022) shows that it is promising to grow fiber hemp, corn and field beans in one field. A field experiment has shown that growing these plants as a multi-crop increases biomass yield, stabilizes gas concentration and emissions from the soil and reduces the proportion of microstructures in the upper soil layer. The biomass of these plants can be a promising raw material for solid biofuels.

To control the quality of pellets, some European countries have developed pellet quality certification regulations and standards, such as the Austrian standard ÖNORM M 7135, the Swedish standard SS 187120, the German standards DIN 51731 and DIN EN 15270, the Italian standard CTI-R04/05, the French recommendation ITEBE (García-Maraver et al., 2011; Picchio et al., 2020). The internationally recognized reference standard is the International Organization for Standardization (ISO) 17225. EN ISO 17225-2 is for wood pellets, while the properties of non-wood pellets, including mixtures, are defined in EN ISO 17225-6 (Rupasinghe et al., 2024).

Biomass combustion, including residential biomass combustion, is a significant source of GHG emissions globally. Biomass combustion is the third largest source of methane (CH_4) contributing to global methane emissions and has a direct impact on the global CH_4 balance due to its long troposphere residence time. Biomass combustion also releases nitrous oxide (N_2O). Reactive nitrogen compounds have a significant impact on atmospheric chemistry. These gases have a greater capacity to absorb and emit terrestrial radiation than CO_2 or CH_4, making them more potent greenhouse gases (Wasilewski et al., 2022).

The aim of this work: to evaluate the quality characteristics of biofuel pellets produced from multi-crop plants (field beans, hemp and maize) and emissions during combustion of these plants.

MATERIALS AND METHODS

The investigated multi-crop plants were grown at the Vytautas Magnus University Agricultural Academy (VMU AA) Experimental Station, in the multi-crop experiment, in the period 2020-2022 (Romaneckas et al., 2023). This article presents the research results of plants grown in 2022. Plants were grown in seven separate fields and were used for research on pressed biofuel production: corn (*Zea mays* L.), fiber hemp (*Cannabis sativa* L.), field beans (*Vicia faba* L.), these are single plants; three binomial plants (various combinations of these plants) and trinomial plans: fiber hemp, maize and field beans (three plants in one field). Plant samples were taken from each field and were chopped, milled into flour and pressed into 6 mm diameter biofuel pellets. The produced 7 types of biofuel pellets were cooled and their most important physical, mechanical, thermal chemical and other properties were tested.

For plant chopping was used drum chopper of forage harvester Maral 125 (Germany). Produced plant chaff was milled using a hummer mill Retsch SM 200 (Germany). At the beginning was determined fractional composition of produced flour by using a Retsch AS 200 sieve shaker (Germany) using sieves with holes of different diameters: 2.0, 1.0, 0.63, 0.5, 0.25 and 0.1. All tests were repeated 3 times. For cylinder pellet production were used a low power granulator (7.5 kW) with a horizontal matrix (Poland).

Biometric properties of pellets, the length and diameter were determined by using a Limit 150 mm digital Vernier caliper (PRC) (accuracy of measurements 0.01 mm). For these experiments were randomly selected 10 pellets of each plant species. For determination of pellet weighed was used balance weights KERN ABJ (Germany) (accuracy of weighting 0.01 g). All tests were repeated 3 times. Pellet volume was calculated, and then pellet density was calculated by dividing the mass to pellet volume.

Pellet strength was determined using an Instron 5965 instrument (USA) and Bluehill software (version 3.11.1209). Test load up to 5 kN, measurement error is 0.02%. The single pellets were placed horizontally on the metal plate of the device and pressed with a semi-dynamic force at a rate of 20 mm per minute until the pellet is damaged. The test was performed on five randomly selected pellets of each sample. The maximum force that the pellet can withstand before the pellet breaks is recorded as the compressive strength value.

The calorific value of investigated pellets was determined by using an automatic calorimeter IKA C6000, the means of calorific value were measured by using the methodology presented in standard LST EN ISO 18125:2017.

Harmful gas emissions when burning pellets (CO, CO_2, NOx and CxHy) were determined using experimental 5 kW solid fuel boiler. All samples of pellets were burned for 7-10 min. and then were measured harmful gas emissions (for this experiment was used the analyzers VE7 and Datatest 400CEM). These experiments were fulfilled by following the standards LST EN 303-5: 2021 and LAND 43-2013.

Analysis of variance of research results were performed to assess the significance of replications using F-test and LSD (probability level – 95%).

RESULTS AND DISCUSSION

The quality of the pellets is influenced by the fineness of the flour particles from which they are made. Before making the pellets, the fractional composition of the flour was determined. The results of the experiment of the fractional composition of the flour are presented in Figure 1.

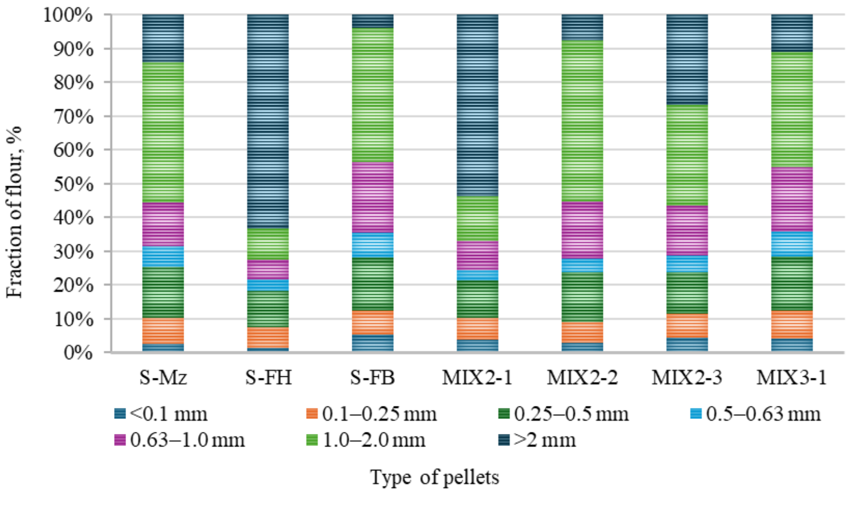

Figure 1. Fractional composition of flour

The coarse fraction of flour (till 2 mm) varied between the S-FH variant (63.3%) and the MIX2-1 variant (53.77%). The second dominant fraction in the studied variants was flour particles of 1–2 mm, which in the five studied variants comprised 29.9–47.7%.

Perez, Dupont and Guillemain (2015) found a trend that the proportion of very large particles (>3 mm) in agrobiomass is significantly lower compared to most woody biomass types (Perez et al., 2015). Studies by Pradhan et al. (2018) also showed that particle size distribution affects energy consumption and compressive strength, but there is no clear effect on pellet bulk density, moisture content, moisture adsorption during storage and abrasion resistance (studies were conducted using a cylindrical die pelletizer with a capacity of 300 kg h^{-1}). The authors indicate that optimal pellet quality is obtained by using a mixture of particles of different sizes, as then a bond is formed between the particles and almost no gaps remain between the particles (Pradhan et al., 2018).

The diameter of all produced pellets was similar – about 6 mm, and varied from 6.1 to 6.2 mm, the length of pellets varied from 22.6 to 25.2 mm. (Figure 2). The length and diameter of the produced granules meet the requirements of the ISO17225-6 standard for solid non-wood biofuels. The parameters of investigated biofuel pellets made by other researchers were very similar. For example, the researcher Ozturk et al. (2019) investigated biofuel pellets and determined, that the average length of pellets was 17.28 mm and diameter 6.26 mm.

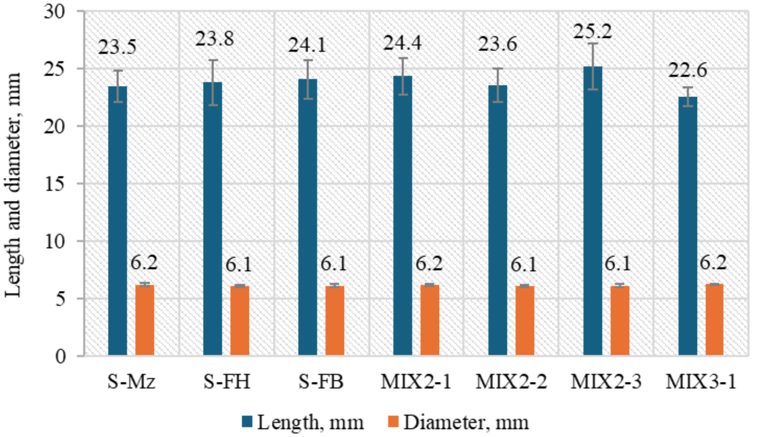

Figure 2. Pellet length and diameter

The results of previous years' research showed that the highest dry mass (DM) density of pellets was for 2020 S-FH pellets (1051.8±30.2 kg m^{-3}) (Figure 3). The lowest density was for 2021 S-Mz pellets (949.6±37.3 kg m^{-3}). Only a few pellet samples had a density below 1000 kg m^{-3}, all other variants had a density above this value. Determined density of 2022 year produced and investigated 7 samples of pellets exceeded 1000 kg m^{-3}, only in the sample S-Mz density was slightly smaller and reached 970 kg m^{-3}.

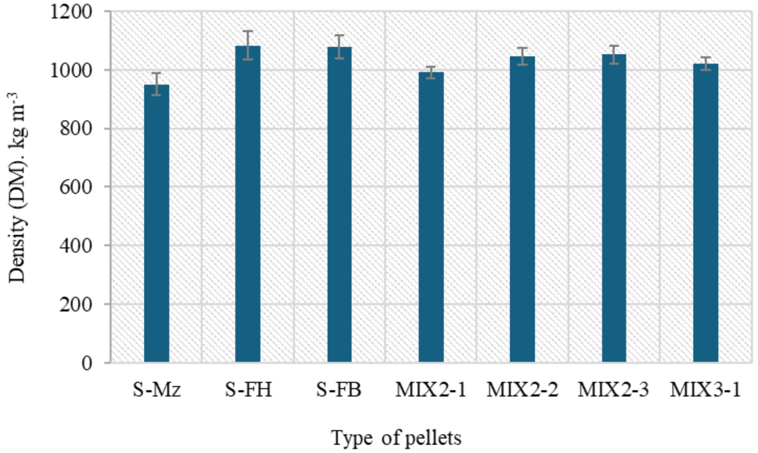

Figure 3. Density of produced pellets (DM)

As stated by Said et al. (2015), the density of pellets made from, for example, rice straw or other biomass can reach 1500 kg m^{-3}, but the recommended value for high quality pellets is 1200 kg m^{-3}. Extremely high pellet density negatively affects combustion efficiency, as in this case the pellet contains oxygen that is more difficult to access (Said et al., 2015).

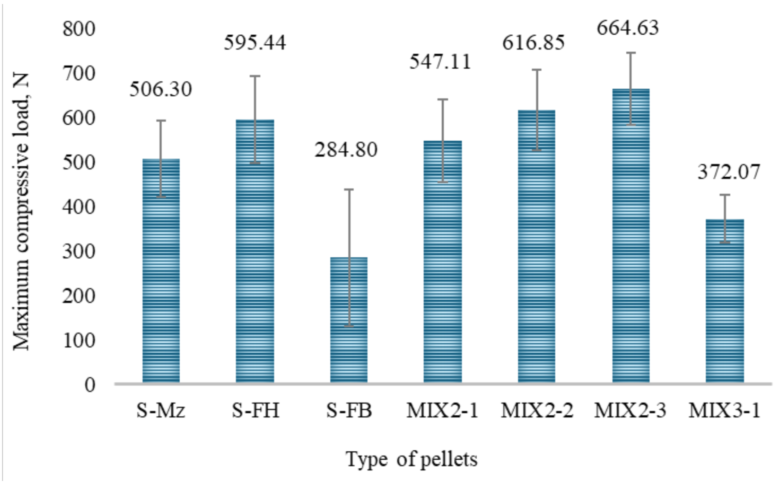

Figure 4. Results of the pellet crushing strength test

Results of produced pellets crushing strength show, that S-FB granules had the least resistance to compression, the maximum force they withstood was 284.8 N. The MIX2-3 granules had the most resistance to compression, they withstood a maximum force of 664.6N (Figure 4).

Using equipment similar to that used in this study by Kambo and Dutta (2014), the strength of untreated miscanthus pellets was determined to be about 320 N, the strength of pellets treated by hydrothermal carbonization methods varied from 200 to 310 N (the authors found that with increasing reaction temperature, the compressive strength of pellets decreased), and the strength of miscanthus biomass pellets treated by the torrefaction method was the lowest and reached only 145 N. It can be stated that the strength of biomass pellets of a polynomial crop in most cases significantly exceeds the strength of miscanthus biomass pellets, regardless of the biomass pretreatment technologies used.

An important parameter characterizing the quality of pellets is their calorific value. Calorific value is defined as the energy released during combustion. The lower calorific value of the seven pellet variants studied is presented in Figure 5.

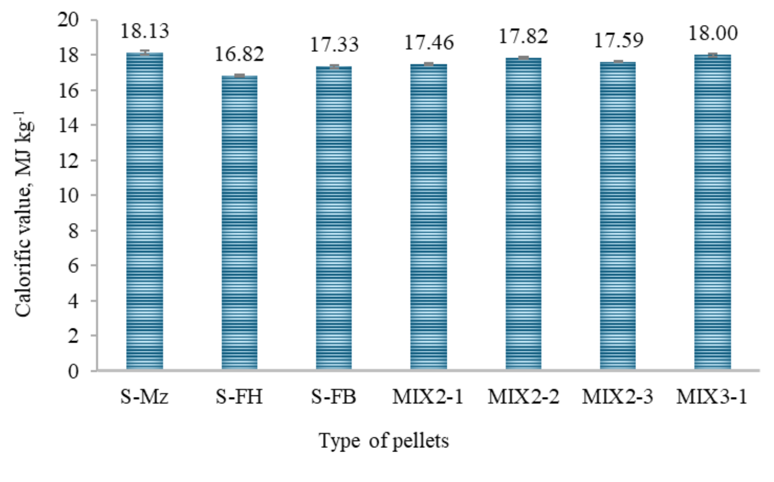

Figure 5. Dry fuel lower calorific value

The highest lower calorific value (18.1±0.10 MJ kg^{-1}) was determined for S-Mz pellets. The lower calorific value of MIX3-1 pellets was only slightly lower (18.0±0.09 MJ kg^{-1}). The lower calorific values of these two pellet variants are close to the calorific value of wood biomass pellets, which, according to Endriss et al. (2023), is typically 18.4–21.3 MJ kg^{-1}.

Harmful emissions during the burning of pellets are also a very important parameter that characterizes their suitability for use. The equipment used for the study of harmful emissions (5 kW stove) can be seen in Figure 6.

The results of determined harmful emissions when burning the pellets of all samples can be seen in Table 1. It can be stated that the lowest CO_2 emissions (5.6%) were determined by burning the biomass pellets of the control sample, wood pellets. The lowest CO, NOx and CxHy emissions, apart from the control sample, were determined when burning Sample S-Mz pellets: 472, 108 and 27 ppm respectively. Finally, it can be stated that the results of the burning and emission studies of all investigated single and multi-crop plant pellets showed that the harmful emissions released into the environment during the burning of pellets did not exceed the permissible norms, and the produced pellets were of high quality and sufficiently strong.

Figure 6. Pellets combustion test: Pellets burned well and burning efficiency was high

Table 1. Harmful emissions by burning pellets

Pellet sample	CO_2 %	CO ppm	NO_x ppm	C_xH_y ppm
S-Mz	3.7	472	108	27
S-FH	3.5	661	119	31
S-FB	4.2	1848	260	161
MIX2-1	3.8	735	142	41
MIX2-2	4.7	871	242	49
MIX2-3	4.2	1625	240	137
MIX3-1	4.0	1689	249	120
Wood pellets	5.6	107	43	13

Research results of other authors (Jasinskas et al., 2020) when burning field bean pellets suggested, that CO_2 emissions reached 4.1–5.0%, CO emissions 1072–2785 ppm, and NOx emissions reached 133–266 ppm. Presented results of Ozturk et al. (2019) show, that when burning the pellets from corn stalks determined CO_2, NO and NOx emission values were 4.7, 38 and 40 ppm, respectively.

Some studies by other researchers show that the use of different biomass mixtures can reduce harmful gas emissions. Dragutinović et al. (2021) found, that when using mix 50% of wood and 50% of corn cob pellets, can be reduced total CO emissions to 60–89%, compared to emissions using only corn cob pellets.

All the determined harmful emissions when burning these investigated multi-crop plant pellets were in the allowed values, and this pressed solid biofuel can be recommended to use for energy purposes separately and in mixtures together with wood and other plants.

CONCLUSIONS

The research results of investigated pellets, which were produced from 7 types of biomass raw materials (fibrous hemp, maize and faba bean) grown individually and as multi-crop plants, are presented in this paper. For comparison also was produced and investigated wood pellets. For pellet production plant biomass was chopped and milled, and it was determined the fractional composition of produced mill in all four samples: 55–70% of mill particle size was less than 2.0 mm. There were determined physical-mechanical properties of produced pellets, such as the length, diameter, bulk density and lower calorific value show, that they meet the requirements of the standard. Determined diameter of pellets was about 6 mm and varied from 6.1 to 6.2 mm, pellet length varied from 22.6 to 25.2 mm. Density of investigated pellets exceeded 1000 kg m^{-3}, only in the sample S-Mz was slightly smaller. After testing the strength of investigated multi-crop pellets during their compression, it was found that the least resistant to compression were the S-FB pellets (the maximum force reached 284.8 N). Pellets MIX2-3 were the most resistant to compression, they even withstood a maximum force of 664.6 N. The lower calorific value of investigated multi-crop pellets varied from 16.82 to 18.13 MJ kg^{-1}. The lowest CO_2 emissions (5.6%) were determined by burning the biomass pellets of the control sample, wood pellets. The lowest CO, NOx and CxHy emissions, were determined when burning Sample S-Mz pellets: 472, 108 and 27 ppm respectively. Determined harmful emissions, when burning not wood but other pellets of plant origin did not exceed the permissible values.

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50. ACTUAL TASKS ON AGRICULTURAL ENGINEERING

Original scientific paper

BIOMETHANE POTENTIALS IN SERBIA - OPPORTUNITIES TO DECARBONIZE ENERGY MIX

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ABSTRACT

Among other goals of the European Green Deal, decarbonization is one of the priorities in almost all sectors across European countries. Biomethane is considered as an alternative for natural gas and an instrument for the decarbonization process, also with other positive for the sectors of agriculture, waste management, energy, (circular-) bioeconomy, etc. Feedstocks' potential to produce biomethane in Serbia and resulting effects with respect natural gas replacement for the time horizons of 2030 (mid-term) and 2050 (long-term) were investigated within this paper. Considered feedstocks originated primarily from agriculture, but from the food industry, commercial and municipal sector, and forestry as well. The three different scenarios concerning feedstock availability and possibilities for their mobilization, as well as the introduction of innovative technologies were considered (conservative, expected, optimistic). Mid-term potentials rate between approximately 500 and 960 ktoe, which is sufficient to replace 17-32% of total domestic natural gas consumption in Serbia. Long-term potentials between 670 and 2,500 ktoe could replace 23-88% of domestic natural gas consumption. Tasks for further research are to investigate different scenarios of the national targets for biomethane production and natural gas substitution across sectors such as transport, energy, commercial, households and agriculture.

Keywords: *feedstocks, potentials, biomethane, decarbonization, effects, Serbia*

INTRODUCTION

Biomethane sectors in many countries have been established based on the existing biogas sectors. Therefore, in the following is elaborated the biogas sector in Serbia. The total number of biogas production facilities that were in operation in the Republic of Serbia (RS) at the beginning of 2024 is 35, with a total power of 34.8 MW_e (range 250-3,570 kW_e, average 996 kW_e). This refers to plants that generate and deliver electricity to the public grid at a subsidized price. In addition, 3 biogas plants with a total capacity of 3,428 kW_e terminated their contracts and ceased operation, whereby 7 produced biogas and used it as an energy source for wastewater treatment plants (WWTP). During 2023, the total amount of produced biogas in Serbia was 111 MNm^3 (for electricity generation and other purposes), and the methane contained in the biogas was 58.1 MNm^3.

During the same year, plants that utilize biogas in cogeneration delivered 227,671 MWh of electricity to the public grid, with the average capacity utilization of 71% because of operational stoppages or insufficient feedstock amount. Of the feedstocks used, animal manure dominated by mass share with 56%, followed by energy crops including sequential crops and organic waste with about 20% each, while crop residues represented 3%. The energy share was the highest from energy crops including sequential crops with 35%, organic waste 34% and manure 24%, while the remaining 7% are crop residues (cereal straw and corn stover). Therefore, the mentioned biogas plants are almost exclusively of agricultural type, where various types of by-products and organic waste are disposed of as well, to replace energy crops, from the following industries: sugar, oil, starch, dairy, potato processing, alcohol, confectionery, *etc*. The stated amount of energy crops was produced on a maximum of 5,000 ha (0.15%) of agricultural land in Serbia, which is a low percentage, but a favorable way to market agricultural products and generate income. Slaughterhouse waste was used as a feedstock in only one plant in the amount of about 3,000 t/a. The represented technology of all the biogas plants is based on wet digestion process (dry matter content in the digester below 12%), in a (semi-) continuous operation, with a mesophilic temperature regime (38-42 °C). The absence of technology based on dry digestion with a batch (discontinuous) process, which is typical for the disposal of municipal biodegradable waste, but also of organic waste from the food industry, confirms the fact that these facilities are of the agricultural type.

Of the 7 biogas plants that do not generate electricity and deliver it in the public grid, one serves for stabilization of organic matter in the sludge from food industry wastewater treatment and 6 for sewage sludge treatment. The produced biogas was used in cogeneration to obtain electricity and heat energy for process energy demand at the wastewater treatment plant ("water line") and stabilization of organic matter ("sludge line"), or as an energy source to obtain heat energy and partially substitute natural gas.

The number of biogas plants under planning and construction is 66, with a total planned power of around 66 MW_e. It is expected that not all potential biogas projects intended for electricity generation will be constructed and there is an opportunity to develop biomethane projects based on them. There is currently no biomethane production plant in operation in Serbia. There is only one project currently under construction with a planned capacity of 625 Nm^3CH_4/h (energy equivalent to the biogas plant of 2.5 MW_e). The facility is intended to produce liquefied biomethane (bio-LNG), along with liquefied carbon dioxide.

Potentials for biomethane production in Serbia were elaborated within several studies. In the report of ENGIE (2021), the long-term potentials for 2050 in Serbia rated 1.77 Mtoe. Grant Thornton (2024) reported the potential of 0.5 Mtoe in 2045 and 0.36 Mtoe in 2045. Martinov *et al.* (2020) determined sustainable biomethane potential in Serbia of up to 206 ktoe/a. In another study investigating biomethane potential in Vojvodina, an agricultural region in Serbia, the theoretical (total) potential from corn stover was about 660 ktoe

(Djatkov *et al.*, 2015). In the same study, the three scenarios for corn stover mobilization to produce biomethane in co-digestion with manure rated 20, 40, and 90 ktoe.

Feedstocks' potential to produce biomethane in Serbia and resulting effects with respect natural gas replacement for the time horizons of 2030 (mid-term) and 2050 (long-term) were investigated within this paper. The potential effects of natural gas substitution by biomethane were elaborated as well. The motivation was to assess the sustainable feedstock potentials, as a basis to define national targets to produce biomethane as an opportunity to substitute fossil resources and decarbonize energy mix in Serbia.

MATERIALS AND METHODS

Materials

Since there are currently no biomethane production plants in Serbia, the feedstock potential determined within this study refers only for future potential plants. Existing biogas plants for electricity generation have already utilized a certain amount of total feedstock potential, and their intended conversion to biomethane production facilities after the expiration of contracts for remuneration for electricity delivery to the grid is considered as a special type of potential. Four levels of potential were evaluated for the considered feedstocks: 1) Theoretical: total amount; 2) Technical: dependent on the possibilities for collection, applied logistical approach, availability, *etc.*; 3) Sustainable: includes socio-economic and/or environmental criteria; 4) For biomethane: determined after considering competitive uses, either for energy or other purposes.

The biomethane potentials were defined considering the two time horizons: 2030 (mid-term) and 2050 (long-term), to analyze opportunities for natural gas substitution in the process of decarbonization in Serbia. To determine the types of determined biomethane potentials (advanced, non-advanced), the Annex IX (Lists A and B) of the REDII (EC, 2018) were used. Figures related to natural gas (import, final and total consumption) were sourced from Integrated National Energy and Climate Plan of the Republic of Serbia– INECP (MMERS, 2024a). To simulate future sector development, the three different approaches were used to determine biomethane potentials and the following scenarios were obtained: conservative, expected, and optimistic.

Methods

Manure

Total production in Serbia amounts to 16.70 Mt/a of solid manure and 11.23 Mm^3/a of liquid manure (theoretical potential). The potential for biomethane is 0.29 Mt/a originating from solid and 3.17 Mm^3/a from liquid manure. These figures, as presented below, were recalculated from national statistical data (SORS, 2021) and previous research on manure in Serbia (Viskovic *et al.*, 2022). The potential for biomethane production includes manure from farms (cattle, pigs, poultry– broilers) with more than 500 cattle units (CU = animals weighing 500 kg) and the amount of manure used in existing biogas plants with opportunity for reconstruction to biomethane production facilities. These figures refer to conservative potentials. Optimistic potentials for the mid-term period assume the collection of 100% of the manure from farms with 50 to 100 CU. Conservative potentials for the long-term period suggest that 25% of the manure from farms with 20 to 50 CU will be used for biogas production, while the expected 50%, and for the optimistic scenario 100% of this type of manure along with poultry manure from farms with more than 100 CU. Manure is the most important feedstock that should form the basis of the biomethane sector, primarily because it ensures the sustainability of production through GHG emissions savings.

Energy crops

The analysis of the potential for energy crops was based on maize silage, which has the highest energy yield per unit of agricultural land area, with a well-established production and logistical chain. The assumption for the conservative potential was that 40% of the dry matter from maize silage will be used in a mixture with manure (the restriction applied so far to the existing biogas plants in Serbia). For the expected potentials, the assumption was 45% of the dry matter share, while for the optimistic potentials 50%. Based on the data from the Statistical Office of Serbia (SORS, 2023), according to the long-term conservative potential, it would be necessary to use 3.2%-4.5% of the used agricultural land in Serbia. These values would increase proportionally if the impact of climate change on the expected yield reduction in 2050 was considered.

Sequential crops

This potential includes the silage production of triticale and rye on the same agricultural area as maize silage. Half of the area would be used for rye, while the other half for triticale. The principle is to use the same agricultural area, achieving lower production costs, however with lower biomass and biogas yields. The approach used assumed that the sequential crops will be grown by farmers who already produce maize silage for biogas production.

Crop residues

Crop residues (agricultural biomass) are the most important biomass potential in Serbia. However, the use of lignocellulosic biomass in the anaerobic digestion process requires energy-intensive and costly pretreatment technology. The total potential was defined based on the yields of field crops and data from literature, allowing the calculation of residue mass based on the mass of the grain (SORS, 2020; Scarlat et al., 2010). Technical potential is the amount that can be collected from the fields, considering losses and the characteristics of the residues (moisture content, contamination) (Martinov et al., 2019). The sustainable potential is the amount that can be removed from the field without negative effects on the soil fertility (40%). The potential for biomethane is from farms with a minimum of 5 hectares. An allocation of crop residues for other uses in the future was also carried out. These include bedding in livestock production of 615,000 t/a of dry wheat straw (Viskovic et al., 2022), as well as 60,000 t/a of dry wheat straw and 140,000 t/a of dry soybean straw for household heating. A competitive use is also the biofuels production from lignocellulosic biomass, such as bioethanol needing 150,000 t/a of dry wheat straw and 100,000 t/a of dry corn stover.

Landfill gas

The analysis of the potential for biogas production from municipal waste landfills considered minimum economic and technical criteria. Landfills were evaluated based on their capacity for extracting at least 125 Nm3CH4/h, or 250 Nm3/h of landfill gas, equivalent to a cogeneration plant of approximately 500 kWe. Additionally, the requirements of the Waste Management Program (MEPRS, 2022), were incorporated, which requires a reduction in biodegradable waste disposal at landfills (to 75% by 2028, 50% by 2032, and 65% by 2039 compared to the 2008 baseline). By 2030, a larger number of landfills are expected to meet the minimum criteria, increasing the potential for biogas production. By 2050, full implementation of waste reduction plans is expected, further decreasing the number of landfills meeting the minimum economic criteria for biomethane production.

Sewage sludge

Biomethane potential from sewage sludge was estimated using the literature source (Martinov et al., 2020). The theoretical potential is relevant for the total equivalent population (EP) in Serbia that is 7.15 million. The technical potential is determined for plants covering a minimum of 10,000 EP, while the sustainable potential for a minimum of 50,000 EP. The potential for biomethane was determined based on the assumption that biomethane would only be produced at the largest facilities, in total 2.74 million EP. The general approach to consider biomethane production from sewage sludge assumed the established practice of using the produced biogas at such plants to meet their own energy needs (electricity and heat), both for the "water line" (WWTP) and the "sludge line" (biogas plant). For the mid-term period, it was assumed that WWTPs with more than 150,000 EP will be built. Optimistic potentials assumed that all the largest WWTPs, with a total capacity of 2.74 MEP, will be used for biomethane production. For the long-term period, it was assumed that all planned WWTPs will be built. Optimistic potentials involved the construction of a "sludge line" at plants with over 50,000 EP, while for those over 10,000 EP, sludge would be collected centrally and treated on a "sludge line."

Slaughterhouse waste

The basis for determining potential was previous research (Martinov et al., 2020), adapted and recalculated for biomethane production. So far, slaughterhouse waste in Serbia has only been used at a single biogas plant. Therefore, practically the entire amount of slaughterhouse waste could be used in the future at plants for biomethane production. This represents a unified theoretical, technical, and sustainable potential for biomethane. Both time horizons were considered equally. Conservative potentials assumed that 25% of the slaughterhouse waste potential will be utilized for biomethane production, expected 50%, and optimistic 75%. The remaining amount of the slaughterhouse waste would be disposed of by alternative methods.

Kitchen waste

Sectoral studies generated the following information related to the food waste amounts: commercial sector 432,000 t/a, of which the food industry generates 261,000 t/a, the HORECA (Hotel-Restaurant-Catering) sector 108,000 t/a, and retail 63,000 t/a (EIC, 2021; CECC, 2020; NALED, 2019). About 170,000 t/a of food industry waste has been already disposed of in the existing biogas plants in Serbia. The main assumption for determining potentials for the two time horizons was that most of this type of organic waste will be processed by anaerobic digestion, i.e. in biomethane production facilities, and that the future waste generation will increase.

OFMSW – Organic Fraction of Municipal Solid Waste

The Waste Management Program (MEPRS, 2022) mandates a gradual reduction in the landfilling of biodegradable waste and its redirection to other treatment and utilization methods, to reduce GHG emissions and ensure more rational use of natural resources. It is estimated that households currently generate 468,000 t/a of food waste, but without primary waste separate collection, transport, and disposal in Serbia. The sustainable potential is the quantity not allowed to be landfilled in 2030, amounting to 801,263 t/a. The potential for biomethane was assumed to be the remaining quantity after utilizing 340,000 t/a at the Vinča incineration plant (30 MWe and 56.5 MWt for district heating). An additional assumption was that a significant share of this type of waste will already be redirected to composting.

Biogas plants

Existing biogas plants in Serbia that utilize biogas to generate electricity represent infrastructure for the disposal of organic waste and by-products, with well-established logistical chains and good practices of anaerobic digestion. After the expiry of the contracts for subsidized electricity price, it was assumed that the most biogas plant owners would be interested in reconstructing their plants to biomethane production facilities. The realization of this would depend on various factors, such as profitability, suitability of existing capacity, conditions for connection to the natural gas network, and the marketability of biomethane with adequate financial remuneration. For the mid-term, the total capacity of biogas plants with 11.2 MWe would be available to reconstruct into biomethane production facilities, and for the long-term 64.8 MWe. Conservative potentials assumed 30% utilization rate of these capacities for the mid- and long-term, while for the short term, it is limited to the first plant constructed in Serbia with a capacity of 635 kWe. Expected potentials assumed 50% utilization, while optimistic potentials assume 70%.

BioCO_2

Biogenic CO2, obtained from purifying biogas by separating CO2 i CH4 is a potential source for methanation (using CO2 and H2 to produce CH4). Biomethane produced through methanation is considered synthetic methane, also referred to as e-fuel or non-biological origin (NBO) fuel. This type of fuel is expected to gain significance in the future, as demonstrated by the REDIII (EC, 2023) requirement for a minimum share of 2.6% of all types of NBO fuels in the transport sector, and RePowerEU's (EC, 2022) minimum of 5.7%. The implementation of this technology is not anticipated in the mid-term in Serbia. Conservative potentials for 2050 assume 10% utilization of bioCO2 from all previously mentioned sources, expected 30%, and optimistic 50%.

Forest biomass

According to the draft Energy Development Strategy of Serbia (MMERS, 2024b), the technical potential of wood (forest) biomass was estimated at 1,668 ktoe. If one-third remains unutilized, this amounts to approximately 556 ktoe by 2050, with the sustainable potential being the same as the technical. For biomethane, about 30% of the sustainable potential was considered, as wooden biomass can also be used as solid fuel for heating and electricity generation. Conservative potentials assumed no construction of forest biomass gasification and syngas methanation plants. Expected potentials assumed the construction of a plant with a capacity of 100 MW, expressed as the primary energy of biomethane, requiring about 225,000 t/a of dry biomass (97 ktoe). This represents half of the recommended capacity for such technology, but it is assumed that investment costs will decrease by 2050 that is the main limitation. Optimistic potentials assume the construction of a plant with a recommended capacity of 200 MW, requiring 450,000 t/a of dry biomass (193 ktoe). Although the required amount of forest biomass exceeds the sustainable potential, it was assumed that additional logistical chains will be organized for collection.

RESULTS AND DISCUSSION

Biomethane potentials for the two time horizons (2030 and 2050) and the three considered scenarios (conservative, expected, optimistic) are presented in Table 1. The effects of biomethane potentials in substituting natural gas (final consumption, imports, total domestic consumption) are presented as well.

Table 1. Biomethane potentials in Serbia – overview and substitution effects of NG

Unit	2030	2050
	Conservative	
MNm^3/a	531	702
$ktoe_{HHV}/a$	505	668
%, Final consumption NG*	47.9	52.4
%, Import NG*	18.9	24.1
%, Domestic consumption NG*	16.6	23.4
	Expected	
MNm^3/a	756	1,383
$ktoe_{HHV}/a$	719	1,315
%, Final consumption NG*	68.2	103.2
%, Import NG*	26.9	47.5
%, Domestic consumption NG*	23.7	46.2
	Optimistic	
MNm^3/a	1,008	2,626
$ktoe_{HHV}/a$	958	2,492
%, Final consumption NG*	104.1	195.6
%, Import NG*	35.8	90.1
%, Domestic consumption NG*	31.6	87.5

MNm^3: million normal cubic meters; HHV: Higher heating value (calculations based on HHV of biomethane); ktoe: thousand ton of oil equivalent; NG: Natural gas; *: energy indicators from INECP projection for the scenario S.

As shown in Table 2, conservative potentials for biomethane production in the mid-term (2030) are almost entirely (93%) enabled by agricultural feedstocks (manure, energy and sequential crops, crop residues). Although nearly one third of this potential originates from crop residues (32%), this potential should be considered conditionally due to technological limitations explained in the Materials and methods section. The low share of biomethane potential from waste streams is due to the lack of appropriate logistic chains, insufficient infrastructure, and lack of clear strategies for waste-to-energy utilization. To enable this in the future, a cross-sectoral strategy and collaboration among national administration in the energy, environmental, agricultural sectors, *etc.* are required. Biomethane potential could substitute 48-104% of final consumption, 19-36% of import, and 13-30% of total domestic natural gas consumption in 2030, depending on the scenario considered, *i.e.* applied approach to determine potentials.

In contrast, optimistic potentials in the long-term (2050) maximize the utilization of waste, which would account for 45% of the total potential, alongside with agricultural feedstocks at 55%. Biomethane production facilities from waste would be built at locations where waste sources are significant (larger cities), assuming that the waste will not be disposed of through competing processes (e.g. incineration, composting) or landfill gas utilization in cogeneration.

Table 2. Conservative potentials in 2030 – overview of sources for biomethane production

Feedstock	MNm^3CH_4/a	ktoe/a	MWe_{eq}	Share
Manure	129	123	65.1	24.3
Energy crops	137	130	69.0	25.7
Sequential crops	63	60	31.8	11.8
Crop residues	167	159	84.4	31.5
Landfill	16	16	8.3	3.1
Sewage sludge	0	0	0.0	0.0
Slaughterhouse	3	2	1.3	0.5
Kitchen waste	5	5	2.6	1.0
OFMSW	4	4	2.2	0.8
Biogas plants	7	6	3.4	1.3
Total	**531**	**505**	**268**	**100.0**

OFMSW: Organic Fraction of Municipal Solid Waste; Biogas plants: Existing Biogas Plants (electricity generation) to reconstruct in Biomethane Plants.

The largest share of biomethane originating from waste represents that produced using biogenic CO_2 by methanation, which is shown in Table 3 (32%). Innovative technology such as the gasification of residual forest biomass and potentially crop residues combined with methanation would also contribute, though this waste utilization pathway has the drawback since there is no possibility to return nutrients after the process back to agricultural land. Biomethane potential could substitute 52-196% of final consumption, 24-90% of import, and 23-88% of natural gas total domestic consumption in 2050.

Table 3. Optimistic potentials in 2050 – overview of sources for biomethane production

Feedstock	MNm^3CH_4/a	ktoe/a	MWe_{eq}	Share
Manure	366	348	184.8	14.0
Energy crops	586	557	295.7	22.3
Sequential crops	269	256	136.0	10.3
Crop residues	229	217	115.4	8.7
Landfill	20	19	10.4	0.8
Sewage sludge	36	31	15.5	1.2
Slaughterhouse	8	7	3.9	0.3
Kitchen waste	24	23	12.0	0.9
OFMSW	25	24	12.7	1.0
Biogas plants	90	85	45.4	3.4
bioCO_2	826	784	415.9	31.5
Forest biomass	147	140	74.4	5.6
Total	**2,626**	**2,492**	**1,322**	**100.0**

OFMSW: Organic Fraction of Municipal Solid Waste; Biogas plants: Existing Biogas Plants (electricity generation) to reconstruct in Biomethane Plants; bioCO_2: CO_2 source from biogas purification to produce biomethane by methanation.

Table 4 gives an overview of share of optimistic biomethane potentials from individual feedstocks or sources, whereby they are classified according to the REDII directive. Biomethane produced using maize silage is classified as non-advanced, since it is food/feed feedstock type. All other biomethane potentials originate from feedstocks listed in Annex IX (Lists A and B) of the REDII. Biomethane produced using feedstocks from these two lists is considered as advanced and can be double counted (calculated with a multiplier) if used in the transport sector. However, according to REDII there are limitations for shares in total energy in the transport sector: non-advanced, a maximum of 7%; advanced from List A, a minimum of 3.5%; and List B, a maximum of 1.7%. These limitations should be respected when defining the national biomethane production targets.

Table 4. Optimistic biomethane potentials - classification according to REDII (Annex A/B)

Feedstock/Source	%, 2030	%, 2050	Type	Remark
Energy crops	29.4	22.3	–	Non advanced[2]
Biogas plants 1G[1]	0.5	1.2		
Manure	18.4	14.0	A	Advanced[3]
Sequential crops	13.5	10.3		
Crop residues	28.3	8.7		
Landfill	4.3	0.8		
Sewage sludge	1.5	1.2		
Forest biomass	0.0	5.6		
Kitchen waste	1.0	0.9		
OFMSW	1.2	1.0		
Biogas plants 2G-A[1]	1.0	2.2		
Biogas plants 2G-B[1]	0.03	0.1	B	Advanced[3]
Slaughterhouse waste	0.8	0.3		
Bio-CO_2	0.0	31.5	e-fuel	Advanced[3]

Biogas plants: Existing Biogas Plants (electricity generation) to reconstruct in Biomethane Plants; OFMSW: Organic Fraction of Municipal Solid Waste; 1: obtained by recalculating the feedstocks used for biogas production in existing biogas plants; 2: Biomethane produced from food and feed feedstocks (non-double counting in transport); 3: Biomethane produced from non-food and non-feed feedstocks (double counting in transport); e-fuel: synthetic fuel (obtained from electricity, mainly for hydrogen used in methanation).

CONCLUSIONS

The possibilities of biomethane production using feedstocks from agriculture, food industry, commercial and municipal sector, and forestry as well in Serbia were investigated. Two different time horizons overlapping with decarbonization deadlines have been considered, *i.e.* 2030 as mid-term and 2050 as long-term. This was the basis to analyze the resulting effects with respect natural gas substitution by biomethane as a renewable energy carrier in Serbia. Agriculture is the sector that could primarily provide feedstocks for biomethane production, particularly in mid-term. Organic waste could not be effectively mobilized and disposed of by anaerobic digestion and simultaneously to produce biomethane up to 2030. Needed prerequisites are facilitated appropriate logistic chains and infrastructure that are still missing in Serbia, as well as significant effort and activities of relevant players across multiple sectors that result in an unambiguous framework and effective implementation in this case in the field of waste-to-energy utilization. This could be expected only in the long-term in Serbia, which is reflected through more significant contribution of waste in the determined potentials. However, even in this case agriculture remains the dominant feedstock source for biomethane production. Potentials for biomethane production in Serbia are significant, since even by applying the conservative approach to consider mid-term effects, nearly half of the domestic natural gas final energy consumption could be substituted by biomethane. Further, around 90% of both import and the total domestic consumption of natural gas in Serbia could be substituted by biomethane, when considering optimistic scenario in long-term. The recommendation is to apply the obtained results within this study related to the biomethane potentials to define national targets for biomethane production in 2030 and 2050 in Serbia. This should subsume consideration of mobilization potential of certain feedstocks, technological and anaerobic digestion process limitations, share of individual feedstocks in the total mixture to meet GHG emission reduction criteria, *etc*. Thus, the appropriate approach in developing national biomethane strategies would be respected. Further research should include investigation of different scenarios of the national targets for biomethane production. Consequently, relevant effects of biomethane utilization across diverse sectors such as transport, energy, commercial, households and agriculture are to be analyzed. This would provide appropriate basis for further development and monitoring of decarbonization process in Serbia in the field of natural gas substitution.

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THE RESULTS OF BIOGAS SECTOR IN SERBIA IN 2023

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ABSTRACT

Introduction of an incentive scheme for renewable energy sources, like biogas, requires good understanding of the technical and financial aspects of the technology. Possibility for biogas sector in Serbia is to transform itself into the biomethane producer. Advantage for policy makers in Serbia is existence of data generated during 12 years of operation of the biogas plants. For example, in this paper are presented some results of the sector in 2023: Average rate of produced electricity was 74%, Average incentivized price of electricity was 20,2 c€/kWh, 472 kt of manure is treated, while 96% of reported industrial organic waste was used by biogas plants. The average GHG emission saving of the electricity produced from biogas is app. 70%, and more than 60% of the plants could be assessed as excellent or good in performance. The results of the sector presented here could be important source for analysis and development of the new incentive schemes for biogas sector by policy makers in Serbia.

Keywords: *Biogas, electricity, evaluation, performances*

INTRODUCTION

The Feed-in tariff for construction of biogas plants in Serbia was initiated by the first Regulation on incentive measures to produce electricity using renewable energy sources in 2009 (MMERS, 2009). This incentive scheme lasted from 2010 until 2020 when it was banned and replaced by a hybrid model of the Renewable energy law and accompanying by-laws (MMERS, 2021). This new model is combination of Feed-in tariff for small biogas plants and tenders for other projects.

The result of the incentive scheme applied is 35 operational biogas plants (4 biogas plants aren't operational anymore) at 28 locations by the end of 2023. They supply electricity into the public grid, treat significant amounts of manure and waste, generate market for energy plants and directly and indirectly employ several hundreds of people. By the end of 2025, several new plants will be finished which obtained temporary privileged producer statuses based on the old incentive scheme.

In 2024 first biogas plants came to the end of incentive period (it lasted for 12 years), so biogas sector in Serbia is at the verging point where these operational biogas plants need to find their place in the future energy and waste management systems. The end of incentives for electricity production represents a threat to the economic viability of the project if operational costs are high and can lead to end of the biogas plant. Addressing this issue is of particular importance when the biogas sector is a significant actor in waste management and manure treatment (Cassaso *et al*, 2021).

Biogas/biomethane production is still highly dependent on incentive measures mainly due to energy plants prices (Kralik *et al*, 2023; Viskovic *et al*, 2023). Nevertheless, REPowerEU establishes a production goal of 35 billion m^3 of biomethane by 2030 in EU (EC, 2022). Each of the EU27 members should contribute to the fulfillment of this goal and that is why the question of new incentive schemes for biogas/biomethane production is very active. Many countries have already introduced new complex incentive schemes for biomethane. e.g. Italy, Denmark, France, but many others are still looking for best options for support of biogas/biomethane sector. Provision of data and parameters for determination of best incentive schemes for future biogas/biomethane production has become an important step in complex analysis and introduction of adequate incentive schemes by policy makers. Many different factors are in the scope of such analysis (Schmid *et al*, 2019; Sulewski *et al*, 2023). For example, available technology (Hashemi *et al*, 2024; Ceilechair *et al*, 2023), natural gas supply security (Thran *et al*, 2023), mitigation of greenhouse gases (GHG) (Negro *et al*, 2025; Ferrari *et al*, 2024). An important advantage for policy makers represents the fact that the biogas sector can provide lots of raw data for analysis and that selection of future unrealistic effects of biomethane production, in terms of goals, can be avoided.

The objective of this paper is to provide the results of the biogas sector in terms of effects on energy generation and waste treatment and to provide a general overview about performance of the whole sector in Serbia.

MATERIALS AND METHODS

Material

As a source for raw data about energy and material flows of biogas plants are used Yearly reports of individual biogas plants, obtained from the Ministry of Mining and Energy. These documents are obligatory reports towards the ministry where individual biogas plant demonstrates fulfilment of conditions for incentivized electricity production defined by law (MMERS 2014a, 2014b). Due to confidentiality of the data, these data won’t be presented here, but only selected results of the analysis.

In total, 33 yearly reports are analyzed from 35 biogas plants. For two biogas plants it wasn’t possible to obtain official data, but in terms of installed capacity and expected impact on the results, these two plants were neglected.

Method

The following parameters were chosen to be presented as a result of the biogas sector in 2023:

- Average rate of produced electricity,
- Average incentivized price of electricity,
- Quantity and characteristics of treated manure,
- Rate of waste treatment,
- Average GHG emission saving of the electricity produced from biogas,
- Performance assessment of individual biogas plant.

The average rate of produced electricity is calculated according to equation 1. Maximal electricity delivered to the network is calculated based on the permitted capacity of every individual biogas plant obtained from publicly available Decisions issued by the Ministry (https://arhiva.mre.gov.rs/doc/registar-250121.html#null) and 8.600 h as a maximal working hour permitted by law (MMERS 2014a, 2014b). For the biogas plant that started operation in 2023, working hours were determined from the date when production started.

$$\text{Average rate of produced electricity [\%]} = \frac{\text{Electricity delivered to the network}}{\text{Maximal electricity delivered to the network}} \quad [1]$$

Average incentivized price of electricity is calculated according to equation 2.

$$\text{Average incentivized price of electricity [c€/kWh]} = \frac{\text{Total income}}{\text{Electricity delivered to the network}} \quad [2]$$

The total income of the entire sector in 2023 is based on data about approved Feed-in tariff of the individual plant and their electricity delivered to the network. These data are legally forbidden to be published so they won't be presented here.

Raw data about quantities and origins of treated manure in the plants is systematized and presented per category of animals and type of manure (liquid and solid). Characteristic dry matter content of the different types of manure normal for Serbian farm conditions is used to calculate quantities of treated dry matter quantities.

Raw data about quantities and origins of organic wastes treated in the plants is used to determine the rate of waste treatment. The quantity of treated waste is divided by total organic waste suitable for treatment. As a waste suitable for treatment by AD, is selected 2nd chapter of the European Waste Catalogue, codes that have starting number 2 – Wastes from agriculture, horticulture, aquaculture, forestry, hunting and fishing, food preparation and processing. Data about total waste quantities suitable for AD are selected from the official Report on waste management in Republic of Serbia 2011-2023 (MEP, 2024).

Average GHG emission saving of the electricity produced from biogas represents average value for every individual biogas plant. For individual biogas plant, GHG emission saving is calculated in accordance with official methodology introduced by Renewable energy directive (RED) (EC, 2018). All substrates are divided into four categories with characteristics presented in Table 1. The method is strictly applied, following instructions from examples presented in Giuntoli et al (2015).

Table 1. Properties of substrates for biogas production

Substrate	DM content, %	ODM content, %	Biogas yield, $Nm^3/tODM$	Methane content, % (v/v)
Energy plants	33	96	663	52
Manure	17	70	364	55
Harvest residues	85	95	310	50
Waste	20	90	1111	55

Performance assessment of individual biogas plants is made by combining results of the Rate of electricity produced and GHG emission saving for every biogas plant. Results are presented at the Scatter diagram where the results for the Average rate of electricity produce and the Average GHG emission savings for entire sector divide the Plot area to four parts: excellent, good, satisfying and poor. The affiliation of the individual biogas plant to a specific part of the Plot area is a resulting performance assessment for the analyzed biogas plant.

RESULTS AND DISCUSSION

Rate of produced electricity

Among the 39 biogas plants that since 2012 gained a status of privileged electricity producers, 35 were active in 2023. Total installed capacity of these plants was 34.8 MWe. The smallest biogas plant had an installed capacity of 0.25 MWe, and largest was app 3.6 MWe. More than half of the plants had installed the capacity of app 1 MWe.

The maximal electricity delivered to the network, based on capacity and allowed working hours, that could be delivered to the network was 295.7 GWh. The electricity produced and delivered to the network was slightly more than 227 GWh, which means that the Average rate of produced electricity for the whole sector was slightly above 74%. A lowest rate identified was app. 23%, while six plants had the rate of produced electricity close, and even higher than 99%.

Average incentivized price of electricity

The Feed-in tariffs for biogas plants in Serbia were in the range of 18.5 – 21.5 c€/kWh. Among 35 active biogas plants, 34 were active beneficiaries of this incentive measure.

The average incentivized price of produced, and to network delivered electricity was 20,2 c€/kWh. This price is comparable, for example, with range of highest regulated price in 2023 by public company for electricity distribution EPS (Electro-distribution of Serbia) (Anonymous, 2023). The range of price for so-called “red tariff” was in 2023 app. between 18-25 c€/kWh, which means that biogas plants could be seen as basic producers of electricity for consumers with the highest electricity prices.

Quantity and characteristics of treated manure

In total, 29 biogas plants reported usage of some kind of manure. Different types of cattle manure were present at almost all of them. Only 2 biogas plants that use manure don’t use cattle manure, but combination of poultry and swine manure.

In 2023, app. 472 kt of manure is treated in biogas plants. Five major categories of manure are identified as a type of manure that operators recognize as individual substrate. That is liquid cuttle manure (slurry), solid cattle manure, swine manure which is always in liquid form, and two categories of poultry manure – chicken manure with or without bedding material.

At table 2 is given share of identified categories of manure, based on fresh matter. An expert opinion (based on many consecutive analyses of the authors provided for the biogas plants in Serbia by authors of this paper) is that average dry matter content of the manure mixture in Serbia is 17%. In total, 80 kt of manure's dry matter was treated in Serbia in 2023. Mostly from cattle, then poultry, and at the end, from swine.

Table 2. Share of manure categories - fresh matter based

Substrate	Share, %
Solid cattle manure	38
Liquid cattle manure	32
Swine manure	19
Poultry manure with bedding material	3
Poultry manure without bedding material	8

Rate of waste treatment

Every biogas plant reported the usage of some kind of organic waste. Different types of organic waste are used, and dominantly, this is industrial organic waste with a very small inflow of practically primary selected kitchen waste. Only 1 biogas plant uses exclusively organic waste, and this plant is basically an industrial biogas plant.

In 2023, app. 167 kt of organic waste is treated in biogas plants. Total reported quantity of wastes from agriculture, horticulture, aquaculture, forestry, hunting and fishing, food preparation and processing in Serbia was 174 kt (MEP, 2024). The Rate of waste treatment according to obtained data is app. 96%. Since the total amount of waste (without mining waste) is more than 10 Mt per year (MEP, 2024), around 2% of waste is treated by anaerobic digestion.

Average GHG emission saving of the electricity produced from biogas

GHG emission saving is a parameter that provides measurement of sustainability of produced energy carriers. In Serbian legislation that provided incentive measure in the form of Feed-in tariff, this parameter wasn't introduced. Nevertheless, certain sustainability of the produced electricity from biogas was assured by the introduction of the limit for usage of corn silage. Maximum share of corn silage in the mixture of all used substrates, based on dry matter content, is 40%. This system assures system where substrates like manure or waste materials are basically mandatory and indirectly it provides certain GHG emission savings for electricity in comparison to fossil fuel comparator – 183 gCO2eq/MJ.

The average GHG emission saving of the electricity produced from biogas in Serbia is somewhere between app. 93% and 48% in comparison to fossil fuel comparator. This wide range is the result of two assumptions during calculation. One is that residual emissions of the biogas from digestate are practically zero, while in the second case, maximal emission value for storage of digestate are applied. The actual average value of GHG emission saving is close to 73%. This claim is based on the authors' insight into the construction characteristics of each individual plant e.g. existence of post-fermenters after main fermenters, closed digestate storage, volumes of fermenters and consecutive hydraulic retention times.

When Renewable energy directive (EC, 2018) introduced GHG emission saving as a sustainability criterion, beside method for its calculation, it also made rules about application. The GHG emission savings should be at least 70% in electricity generating plants starting after 01/01/2021 or 80% in plants starting after 01/01/2026, compared to a fossil fuel comparator. Also, this sustainability criterion applies only to biogas plants with a total rated thermal input equal to or exceeding 2 MW, but individual EU member states may also introduce the obligation for smaller biogas plants. Since the average value of GHG emission saving is close to 73%, it could be said that electricity produced from biogas in Serbia is sustainable. Newerthelees, if the individual biogas plant is considered, the range of GHG emission saving value is between 44-121%, so not all of them reach limit of 70% saving.

Performance assessment of individual biogas plant

At Figure 1 is shown Scatter diagram for performance assessment of every operational biogas plant in Serbia. Biogas plants are marked with appropriate code and due to legal issues, their name is not shown. 9 plants can be classified as excellent in performances, 13 as good, 2 as satisfactory and 11 of them have evaluated performance as poor.

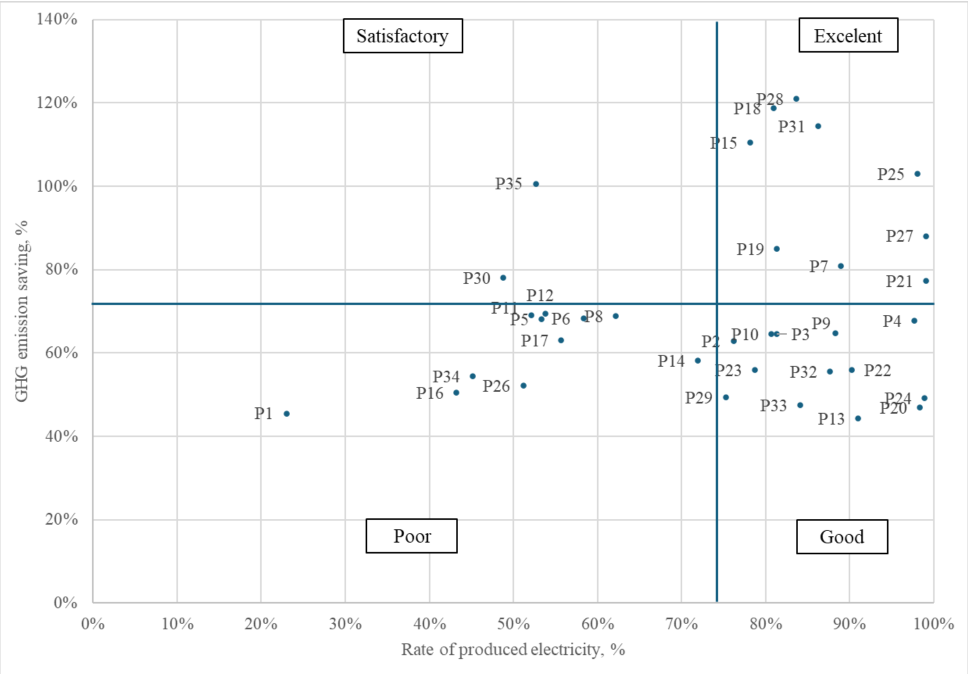

Figure 1. Performance assessment of biogas plants in Serbia

CONCLUSIONS

Biogas sector in Serbia reached peek of the development by ending of the incentive scheme. It doesn't perform at full capacity, but there are many good examples of excellent performance. Further incentives by authorities could be introduced to motivate management of the plants to achieve better performances.

Electricity produced from biogas can be seen as "green" and sustainable in terms of GHG emissions and as a product of circular economy.

This sector emerged as a very important treatment option for many waste streams, especially for the treatment of industrial organic waste, but improvements in terms of specific targeting of some unused waste streams is possible, for example slaughterhouse waste.

The results of the sector presented here about energy generation, substrates treated and GHG emission savings could be an important source for analysis and development of the new incentive schemes for biogas sector by policy makers.

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50. ACTUAL TASKS ON AGRICULTURAL ENGINEERING

Original scientific paper

ALTERNATIVE FUELS FOR DECARBONIZING TRANSPORT SECTOR IN SERBIA

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ABSTRACT

The transport sector significantly contributes to global greenhouse gas (GHG) emissions, primarily due to its reliance on fossil fuels. This paper investigates the potential and impacts of producing alternative fuels in Serbia. The potential for 2030 was assessed for feedstocks from agriculture, food industry, commercial sector, municipal waste, and forestry. Results indicate that the total potential of all feedstocks is approximately 7.6 million tons of fresh mass. Using the considered feedstocks, various types of alternative fuels could be produced, such as biomethane, lignocellulosic bioethanol, hydrotreated vegetable oil, hydrogen, and synthetic fuels. In this way, about 402 ktoe can be obtained from the abovementioned alternative fuels for the transport sector in Serbia. These alternative fuels could meet up to 16% of Serbia's transport energy needs, potentially reducing GHG emissions by 19%.

Keywords: *Alternative fuels, feedstocks, decarbonization, transport sector, Serbia*

INTRODUCTION

The European Union (EU) has been promoting alternative fuels for transport to reduce greenhouse gas (GHG) emissions and decrease reliance on fossil fuels, as outlined in various strategic documents (EC, 2019; 2021; 2022). According to the Regulation (EU) 2023/1804 on the deployment of alternative fuels infrastructure (EC, 2023a), alternative fuels are defined as fuels or energy sources that substitute fossil oil sources in transport and that have the potential to contribute to decarbonization and improve environmental efficiency. These alternative fuels include electricity, hydrogen, biofuels (both conventional and advanced), synthetic and paraffinic fuels, natural gas (including biomethane), and liquefied petroleum gas. The European Green Deal aims to achieve climate neutrality across the European continent by 2050 (EC, 2019). To achieve this goal, GHG emissions in the transport sector are expected to be reduced by 90%. As an intermediate step toward this target, the Renewable Energy Directive (REDIII) outlines a plan for 2030, which includes a minimum share of 29% for renewable energy sources (RES) in the transport sector or a reduction in GHG emissions by 14.5% (EC, 2023b).

Serbia is a member of the Energy Community and has ratified the agreement on the implementation of EU directives in the field of RES, i.e., alternative fuels and their use in the transport sector in the decarbonization process (MMERS, 2006). In addition, Serbia is a signatory of the Sofia Declaration on the Green Agenda for the Western Balkans, in which it undertook to follow EU policy in the areas of the European Green Deal. In the Integrated National Energy and Climate Plan (INECP) (MMERS, 2024a), the target for optimistic scenarios with additional policies and measures is that the share of RES in the transport sector should be 6.8% in 2030, by the relevant EU calculation methodology, or 3.2% without multipliers. For the scenario without additional policies and measures target of 2030 is 5.5%, or 3.7% without multipliers.

The potential of alternative fuels in Serbia has been evaluated in several studies. Martinov et al. (2020) assessed the sustainable biomethane potential in Serbia and estimated that up to 206 ktoe. The potential for biodiesel ranges from 146 to 251 ktoe annually, according to Djurisic-Mladenovic et al. (2018), with only 4% to 7% derived from used cooking oil (UCO). Mojovic et al. (2013) projected that the potential for conventional bioethanol in 2030, utilizing market surplus crops and production on marginal land, could reach approximately 686 ktoe annually. This same study estimated the potential for lignocellulosic bioethanol (LCB) in 2030 to be around 583 ktoe annually. However, these studies did not conduct a comprehensive analysis of the potential for all relevant feedstocks, nor did they evaluate potential alternative fuels in Serbia and the decarbonization effects of their use.

This paper investigates the potential and effects of producing alternative fuels in Serbia, specifically advanced biofuels, biomethane, hydrogen, and synthetic fuels. The aim was to assess the sustainable feedstock potentials available in Serbia for the production of alternative fuels for transportation. A comprehensive methodology was proposed, considering technical, environmental, and socio-economic aspects and criteria. Additionally, the study evaluated the feasibility of achieving decarbonization goals in the transport sector by 2030.

MATERIALS AND METHODS

The mass potential of feedstocks for alternative fuels was assessed using the proposed methodology across five categories: agriculture, food industry, commercial sector, municipal waste, and forest biomass. Further, the methodology to allocate the determined mass potential of feedstocks was to appropriate alternative fuels and to determine their energy potential was elaborated. An assessment approach for the impact of using the potential to decarbonize the transport sector is provided.

Methodology for feedstock potential assessment

Feedstocks from agriculture

Manure: Potential of manure is defined based on research by Viskovic et al. (2021). The theoretical potential of manure is defined as the total amount of manure generated on all farms in Serbia. Compared to previous research, the quantity was reduced for the cattle manure quantity originating from small farms (less than 100 livestock units (LU)), since cattle spend part of the year outside and manure could not be collected. Specifically, it was found that only one-third of straw is used for bedding, compared to the originally assumed 5 kg per day per LU. Also, the ratio of solid and liquid manure obtained from pigs was changed, and solid manure was reduced from the originally assumed 50% to 20% on small farms. The technical potential refers to the quantity of manure produced by farms with over 100 LU, which generates a larger amount of manure that can be effectively utilized as feedstock, such as in biogas plants. Sustainable potential excludes combined farms in municipalities unable to collect 500 LU from technical potential. The potential for alternative fuels is calculated by subtracting the amount used in existing biogas plants (only those operational in 2030) from the sustainable potential. Thus, 60% of the 250 kt of manure can be used for fuel production (about 33% is solid manure). Of the solid manure, 80% is from cattle and 20% from broilers, and of the liquid manure, 60% is from cattle and 40% from pigs.

Crop residues: The theoretical potential of crop residues (wheat, barley, oat, rye, corn, rapeseed, sunflower, and soybean) was assessed using data on annual seed production (2005-2021), yield, and moisture content (SORS, 2022; Eurostat, 2022) and recalculated for Serbia's residue-to-product ratios (Scarlat et al., 2010). The technical potential depends on the equipment used and the condition of crop residues, with specific values for each crop based on agricultural practices in Serbia (Golub et al., 2012; 2013; Veselinov et al., 2015; Martinov et al., 2019). The sustainable potential refers to the amount of residues that can be removed without reducing soil fertility by maintaining organic matter and organic carbon in the soil and protecting it from erosion (Scarlat et al., 2010; Golub et al., 2012; 2013; 2016; Veselinov et al., 2015). Only large farms were considered for alternative fuel potential. For the regions of Vojvodina and Belgrade, farms with plantations of 5 ha and more were considered, whereas for the rest of Serbia, farms with plantations of 10 ha or more were considered due to plot fragmentation, hilly terrain, and other logistical challenges. Crop residues also serve other purposes, such as bedding for cattle and heating. Estimated amounts used for these purposes were deducted from the potential for alternative fuel. For 2030, crop yields are projected to decrease by 10% due to climate impacts, aligning with research findings (Martinov et al., 2019). This reduction affects both grain and residue yields.

Feedstocks from food industry

Food processing: The theoretical potential is unknown due to the large number of sources and the disorganization of the collection and waste registration system. This subcategory includes the meat processing industry, the fruit and vegetable processing industry, the beverage industry, the bakery and confectionery industry, dairies, sugar factories, and markets. Technical potential refers to everything that is collected and recorded by the Serbian Environmental Protection Agency (SEPA, 2023). The sustainable potential and potential for alternative fuels range from 40% to 100% of the technical potential, depending on the feedstock in question. It is assumed that this portion cannot be used for other purposes, i.e., it is available for the production of alternative fuels.

Slaughterhouse waste: The potential determined by Martinov et al. (2020) has been adapted and recalculated for the production of alternative fuels. In Serbia, slaughterhouse waste is used only in one biogas plant, amounting to about 3 kt a^{-1}. Therefore, practically the entire amount of slaughterhouse waste could be used in the future. The total potential is about 8.8 ktoe of biomethane per year. This represents the combined theoretical, technical, and sustainable potential. It is assumed that 25% of slaughterhouse waste will be used for the production of alternative fuels.

Feedstocks from commercial sector

Kitchen waste: The total amount of food waste generated in Serbia is estimated at around 900 kt a^{-1}. Although no comprehensive measurements have been carried out so far to determine the share of different sources of food waste in total quantities, by analyzing the available data, i.e., sector studies, the following data were obtained (EIC, 2021; CECC, 2020; NALED, 2019). The HORECA sector (hotels, restaurants, and catering), which generates 12% of food waste, is the source of kitchen waste in the commercial sector. The main assumption is that most of this kitchen waste (about 50%) will be disposed of adequately, i.e., by application in plants to produce alternative fuels.

Used cooking oil: According to Djurisic-Mladenovic et al. (2018), Serbia uses an estimated 85 kt of edible oil annually, with up to 25% of that amount being potentially collectible post-use, mainly from restaurants and the food industry. Currently, only around 4.5 kt of UCO are collected yearly (SEPA, 2023). The collection system is expected to be improved, particularly in restaurants and the food industry, aiming to achieve at least 50% of the theoretical potential, which constitutes UCO's technical potential. The sustainable and potential for alternative fuels is the same and predicts a slight increase in the level of UCO collection compared to the current level.

Feedstocks from municipal waste

Organic fraction of municipal solid waste: The theoretical potential of the organic fraction of municipal solid waste (OFMSW) is the total biodegradable waste for the year 2030, according to the Waste Management Program in the Republic of Serbia for the period 2022-2031 (MEPRS, 2022). The technical potential is the bio-waste collected in 2030. This potential value has already considered the change in the number of inhabitants, as well as composting in households. The sustainable potential is the difference between the technical potential and the amount of waste that will be deposited. The potential for alternative fuels is reduced by the amount of waste that will be incinerated at the Vinca plant and the share of bio-waste that will be composted at large plants.

Green waste: Part of the green waste from parks and public areas can be composted or used as feedstocks for alternative fuels, such as bio-H_2. It is estimated that about 30% of green waste is generated in large cities (Belgrade, Novi Sad and Niš), and that amount can be used for producing alternative fuels (MEPRS, 2022).

Sewage sludge: The theoretical potential refers to the total number of population equivalents (PE) for the whole of Serbia (MAFWMRS, 2021). Technical potential refers to all plants that are greater than 10,000 PE. Sustainable potential refers to plants that have at least 50,000 PE. The potential for alternative fuels in 2030 was adopted so that only the largest plants were included, i.e., those with more than 150,000 PE, and there would be four such plants.

Feedstocks from forest biomass

According to the Energy Development Strategy of the Republic of Serbia (MMERS, 2015; 2024b), the total potential of forest biomass is estimated to be between 1,530 and 1,668 ktoe. This potential can be considered theoretical. Only one-third of this potential is currently unused and can be considered technical and sustainable. Given that forest biomass can be utilized as a fuel for heating in households and heating plants, as well as for electricity production, the potential for alternative fuels is estimated to be around 30% of the sustainable potential.

Methodology for assessment of alternative fuels potential

In this paper, the allocation of the entire assessed potential of feedstocks for producing various alternative fuels is performed. Feedstocks such as manure, waste from food processing and kitchens, slaughterhouse waste, OFMSW, and sewage sludge are the most suitable for use in biomethane production, as discussed in this paper. Biomethane yields differ for each of these feedstocks and are defined by the literature (LfL, 2024; Scarlat et al., 2018; KTBL, 2010; Martinov et al., 2020). Crop residues are divided so that 45% of straw and 30% of corn stover are used to produce biomethane with defined yields according to the literature (LfL, 2024; Lizasoain et al., 2017). The remaining potential of crop residues is allocated to produce LCB by the defined yields (Sharma et al., 2002; Kim and Dale, 2004; Kahr et al., 2013; Kuglarz et al., 2018; Kim, 2018; Tse et al., 2021;). Additionally, UCO is designated for hydrotreated vegetable oil (HVO) production (Hamelinck et al., 2021). Green waste is designated for the production of green hydrogen by applying adequate technology (HiTES, 2024). The full potential of forest biomass is utilized to produce synthetic fuels using the Fischer-Tropsch process with defined yields (Kreutz et al., 2008; de Jong et al., 2017).

Methodology for assessment of decarbonization effects

To assess the effect of decarbonization, GHG emissions for the considered alternative fuels, as shown in Table 1, were used and compared with the fossil comparator (94 gCO_{2eq} MJ^{-1}), following the methodology outlined in the REDIII Directive. It was assumed that the entire quantity of alternative fuels in 2030 would replace fossil fuels in the transport sector. Electricity was excluded from consideration and subsequently subtracted from the total energy needs of the transport sector when assessing the effect of decarbonization. This approach allows for the evaluation of the energy coverage level with alternative fuels from available feedstocks in Serbia and the extent of decarbonization achieved through their application. Estimates of energy needs in the transport sector align with INECP scenarios. In the scenario without additional policies and measures, known as the With Existing Measures (WEM) scenario, the projected energy needs in the transport sector will be 2,748 ktoe by 2030. Additionally, there are two scenarios with additional policies and measures or With Advanced Measures (WAM) scenarios, labeled scenario S and scenario S-N. The key difference between these scenarios is that scenario S-N includes the introduction of nuclear power plants in Serbia starting in 2040. For 2030, the energy needs are identical for both scenarios (S and S-N), totaling 2,512 ktoe.

Table 1. Emission factors for alternative fuels

Fuel	Emission, gCO_{2eq} MJ^{-1}
Biomethane	-100.0 – 22.3[A, B]
LCB	15.7[A]
HVO	16.0[A]
Hydrogen	12.4[B]
Synthetic fuels	5.2 – 16.7[A, C]

A: EC, 2023b; B: Prussi et al., 2020; C: ICAO, 2022.

RESULTS AND DISCUSSION

Feedstocks potential

The data presented in Table 2 quantifies the potential of various feedstocks for alternative fuels in thousands of tons of fresh mass in 2030. The total potential of feedstock is estimated to be approximately 7.6 Mt of fresh mass or 2.2 Mt of dry mass. When considering both solid and liquid forms, manure emerges as the dominant feedstock, commanding a total share of over 66%. Crop residues, with a share of over 15% or about 1.2 Mt of fresh mass, are the second dominant feedstock. Sewage sludge and forest biomass each contribute approximately 7% to the total potential. Other feedstocks collectively account for less than 6% of the total potential for alternative fuels.

Table 2. Feedstocks potential for alternative fuels

Source	**Mass, kt_{FM} a^{-1}**	**Share, %**
Solid manure	999.9	13.2
Liquid manure	4,025.8	53.1
Crop residues	1,185.0	15.6
Food processing	59.9	0.8
Slaughterhouses	17.3	0.2
Kitchen waste	50.0	0.7
UCO	5.0	0.1
OFMSW	135.5	1.8
Green waste	31.3	0.4
Sewage sludge	548	7.2
Forest biomass	524.3	6.9
TOTAL	**7,582.0**	**100.0**

FM: fresh mass.

Potentials of alternative fuels

If the considered feedstocks were allocated as defined, the energy content of alternative fuels would amount to 402 ktoe (Table 3).

Table 3. Potentials of alternative fuels

Alternative fuels	**Energy, ktoe a^{-1}**	**Share, %**
Biomethane	208.6	51.9
LCB	116.1	28.9
HVO	4.0	0.9
Hydrogen	2.7	0.7
Synthetic fuels	70.6	17.6
TOTAL	**402.0**	**100.0**

About 52% of the alternative fuel potential is biomethane, and more than half of it (over 112 ktoe) is produced from manure. Crop residues are the feedstock that contributes the most energy, with a share of about 45%, yielding more than 179 ktoe of biomethane and LCB. Forest biomass is also an important feedstock for obtaining alternative fuels, with an energy share of over 17%. Alternative fuels from other feedstocks contribute significantly less energy, with their total contribution being less than 10%.

Decarbonization effects

The decarbonization effects of using alternative fuels in the transport sector in Serbia are presented in Table 4. Considering the WAM scenarios, about 16% (without multipliers) of the energy needs could be met, while in the WEM scenario, less than 15% (without multipliers) could be met using alternative fuels. This is five and four times more when comparing the targets from WAM and WEM scenarios. Additionally, the REDIII Directive target (29% with multipliers) would be met in both cases. Utilizing this quantity of alternative fuels instead of fossil fuels could potentially lead to a reduction in GHG emissions by up to 19% in the WAM and WEM scenario. Consequently, the target for reducing GHG emissions by 14.5% by 2030, as set by the REDIII Directive, would be met in both cases.

Table 4. Effects of decarbonization

INECP scenario	WEM	WAM
Energy in transport, ktoe	2,748	2,512
Alternative fuels, ktoe	402.0	402.0
Share of alternative fuels in transport^{A}, %	14.6	16.0
Share of alternative fuels in transport^{B}, %	29.2	32.0
Share of RES^{A}– target, %	3.7	3.2
Share of RES^{B}– target, %	5.5	6.8
GHG emissions savings, %	17.6	19.2

A: without multipliers, B: with multipliers.

CONCLUSIONS

According to the INECP, the 2030 targets for RES in transport can be achieved, as only a portion of the defined potential of alternative fuels needs to be utilized, about 20% for WAM scenarios and 25% for WEM. Therefore, reaching the transport decarbonization target does not require the use of renewable electricity. Only one approach to the feedstocks' allocation for the production of alternative fuels is presented in this paper. Future research should focus on developing various scenarios for allocating feedstock potentials to different relevant alternative fuels and their ranking. The criteria for evaluating these scenarios, based on their suitability for decarbonizing the transport sector in Serbia, should include feedstock availability, the maturity of fuel production technologies (readiness level), the energy production costs of fuels, and the national-level decarbonization effect (potential GHG emission reductions).

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50. ACTUAL TASKS ON AGRICULTURAL ENGINEERING

Expert paper

A COMPARATIVE ANALYSIS OF DOMESTIC BIOMASS COMBUSTION SYSTEMS

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ABSTRACT

The paper proposes a hybrid method for compare actual domestic biomass combustion solutions/systems used in European area. More than 100 domestic biomass combustion solutions/systems where analysed based on 24 criteria system, grouped on construction, safety, function and economic performance, orientated on technological criterion, profitability and environmental protection, and insuring safety functional processes. The biomass combustion systems were selected according to the next conditions: ensuring high quality burning process biomass fuels both for pellets, and other biomass, to enable integrated system application for central heating boilers, to avoid the risk of fire for the entire equipment and the vicinity presents. Firstly, based on primary information about burning system, the similar burners were grouped and the more representative of them were selected. 58 individual solutions of biomass burners were kept for criterial analysis. A matrix that includes the 24 criteria on rows and the 58 individual solutions of biomass burner on columns was used for systems classification and ranking, according to the cumulated points. The refining of the results was realized by simple value analysis. Finally, the best ranked solutions (accomplishing more than 75 % of criteria) were classified according to the combustion bad as follows: 5 solutions based on fix combustion bad, 7 solutions based on mobile combustion bad, and 2 solutions based on fluidised combustion bad. The results constitute a point main base start for next TRIZ application in design of the modern systems for biomass combustion correlated with actual trend of continuous improvement and optimization of such systems existing, with minimum additional costs, based on identification of critical criteria. The essential conclusion of the paper was the *simplicity of proposed method compared to theory of inventive problem solving (TRIZ) and pure value analysis.*

***Keywords**: biomass combustion burner, TRIZ, rank, design optimization*

INTRODUCTION

In recent years, the use of biomass, involves a big concern of research, development and implementation of new suitable solutions to cover the increased energy demand, fossil fuel depletion and to avoid the climate changes (Tucu and Hollerbach, 2011; Tucu, 2012; Filipovici et al., 2017). Consequently, combustion systems have increased significantly in Romania, due to the increased awareness of the negative impact on the environment caused by outdated, traditional combustion systems, their low efficiency, implicitly their costs, but also the abundance biomass in the country (Kazomir and Tucu, 2023). Over the last decade there has been an accelerated increase in demand for wood pellets, pushing demand out of supply and directly influencing price increases. The conditions for biomass production becomes strongly, in conditions of contradictions between law and economic conditions and/or enterprises resources (Tucu et al., 2019). The increased interest for such activities already imposed new and special technologies, both from agriculture and combustion systems, which integrates machinery, technologies and other social rural activities and different approach by general and special methods (Tucu and Filipovici, 2014; Tucu, 2014). With wood biomass pellets becoming both expensive and in short supply, and lower quality pellets, and wood chips becoming more affordable and available, there is an increasing need for burners that can efficiently burn this difficult biomass with reduced system maintenance (Tucki et al., 2019; Krüger and Mutlu, 2021; Kantová et al., 2022; Konieczna et al.,2022; Holubcik et al., 2023; Ciupek and Nadolny, 2024; Dula et al., 2024).

The necessity for new and easy to use tools to quickly compare biomass burning systems increases with the increasing in the number of burners on the market. In the same time, the producers of biomass combustion systems are interested to optimize the manufacturing system by many variables as: type of energy, placement of source, availability, prices at date and strategic trends, local law, environment and other conditions (Tucu et al., 2010).The new tools must also make it easier for manufactures to evaluate biomass burning systems, so that automation and optimization of existing systems becomes a quick and simpler option by designing new burners or integration one existing solution.

In this context, multiple heating options exist, with numerous ramifications for each of them, in conditions for the end user the cost is what matters mainly. From centralized heating, by electric or gas-based systems, heat pumps and central heating systems, with solid fuel, wood or biomass, the choice is guided by the final cost and energy security.

The vast raw material that can be used in pellet burners, densified or chopped, led this research to systematize and compare the information regarding the functional processes in biomass thermal energy conversion systems, so that anyone can easily understand the specific process conditions which are the basis of this technology, easing the choice of constructive solutions in the design or automation of existing systems. Such comparative studies are found in numerous authors who experimentally compare two burners (Rastvorov et al., 2017; Ciupek and Bartoszewicz, 2019; Polonini et. al., 2019; Pelka et al., 2023). Also, the main problem becomes integration of solutions to answer both commercial, industrial and business for all involved parts: integrant, integrated, integrator (Mnerie et. al., 2008).

The main objective of the paper is to design and test a hybrid method for evaluation and comparation of actual domestic biomass combustion solutions/systems, based on literature data. Connected, there are secondary objectives as: identification of the most efficient burners in terms of performance and creating the main base start point for next TRIZ application, based on identification of critical criteria.

METHODS

The succession of methodological steps was created for design the study's workflow included in present paper (figure 1).

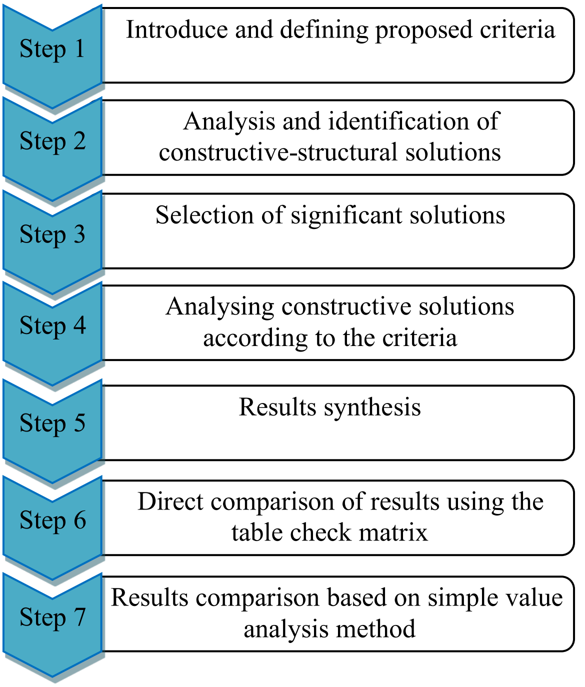

Figure 1. Methodological workflow

The analysis of the selected constructive solutions according to the criteria was conducted and presented using a check matrix. Two assessment levels were used in the matrix: 0-unfulfilled the criteria and 1-satisfied the criteria, with one exception: the lack of data from manufacturers in manuals and technical sheets automatically generate a 0 score for the burner on the associated criterion with the missing data.

Based on the same matrix, the direct comparison of the results was carried out.

Next criteria and levels were proposed (see figure 2): 1-position of burning bad (1.1-tilted; 1.2-horizontal); 2-number of structural elements (2.1-simple (1 element); 2.2-composed (2 or more elements)); 3- shape of combustion chamber (3.1 – simple geometric shape; 3.2-complex geometric shape); 4 – material of combustion chamber (4.1-monomaterial; 4.2-composite); 5-concept (5.1-dedicated; 5.2- hybrid); 6- combustion chamber type (6.1 – tubular vertical (retort); 6.2 – tubular horizontal; 6.3- vertical cup); combustion type (7.1-without gasification; 7.2-with gasification); 8- recirculation (8.1-withoutrecirculation; 8.2-with recirculation); 9-cleaning system (CS) (9.1-without CS; 9.2-with CS); 10 – construction (10.1- monobloc; 10.2- modular); 11- power value (11.1- low (<50 kW); 11.2- middle (51-300kw); 11.3-high (>300kw); 12- powering of carburant supplying system (12.1- gearmotor; 12.2-stepper motor); 13 - construction of supplying system (13.1-screw; 13.2-gravitationally; 13.3-pneumatically; 13.4-mixttury); 14 – supplying type (14.1-free; 14.2-forced); 15 – directing of comburent (15.1-natural convection; 15.2-forced draw); 16 - flame control (16.1-with detecting; 16.2-without detecting); 17 – ignition system (17.1-automatically; 17.2-manual); 18 – gas emission class (18.1-classes 1^{st} -2^{nd} (forbidden); 18.2-classes 3^{rd} - 5^{th} (authorized)); 19 – combustion efficiency (19.1-high (5^{th} class); 19.2-average (4^{th} class); 19.3 – low (3^{rd} class or less)); 20 – protection level against accidents and fire (20.1-high (classes B-C); 20.2 – low (class A)); 21 – Level of automation (21.1-half automation; 21.2-full automation); 22 - process control (22.1-with local controller; 22.2-local and remote controller); 23 – burning flow (23.1-perpendicularly; 23.2-equicurrent; 23.3-countercurrent; 23.4-cyclon; 23.5-mixt); 24 – costs (24.1-reasonable (<3000EUR); 24.2-average (3000-4000EUR); 24.3-high (>4000EUR)).

The burners were classified according to the type of combustion support into three groups (fixed, moving, and fluidized bed), with the groups further divided into subgroups (based on the behaviour and cleaning of the combustion support), into classes (based on the shape of the combustion chamber), into families (determined by the material of the combustion chamber), and ultimately, into types/categories (anchored in the combustion chamber concept). The classification for each burner into a category should follow next format: group-subgroup-class-family-category. Finally, Direct Comparison (DC) and Single Value Analysis (SV) were use simultaneously.

RESULTS

After examining over 100 identified biomass combustion systems (BCS) from the literature and products from market prospects, the previous twenty-four analysis criteria were verified. Based on similar constructive solutions, grouped together (considering all weight of criteria equal to 1), result, finally, selection of 58 representative individual solutions for criteria analysis.

Figure 3 presents the resulted structural-constructive classification of biomass combustion systems, based on figure 2 (which presents the results of the typological classification of biomass combustion systems based on selected 24 individual criteria (including constructive concepts, safety, operational aspects, economic performance and serving as a tool for comparing BCS).

The table check matrix for accomplishment according to proposed criteria regarding technology and construction of biomass combustion burners from figure 2 is presented in table 1.

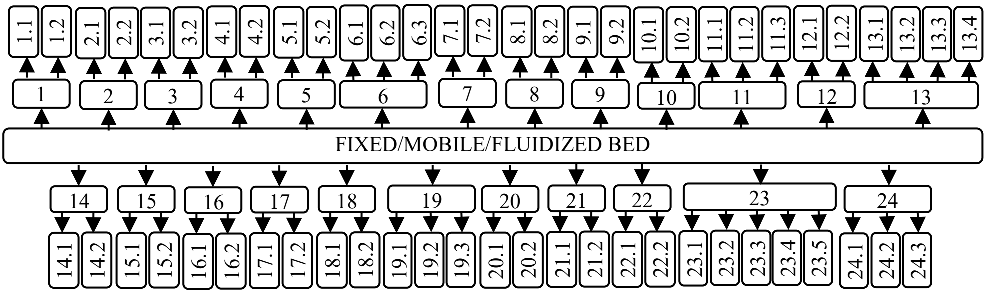

Figure 2. Typological classification of biomass combustion systems with fixed/mobile/fluidized combustion bed

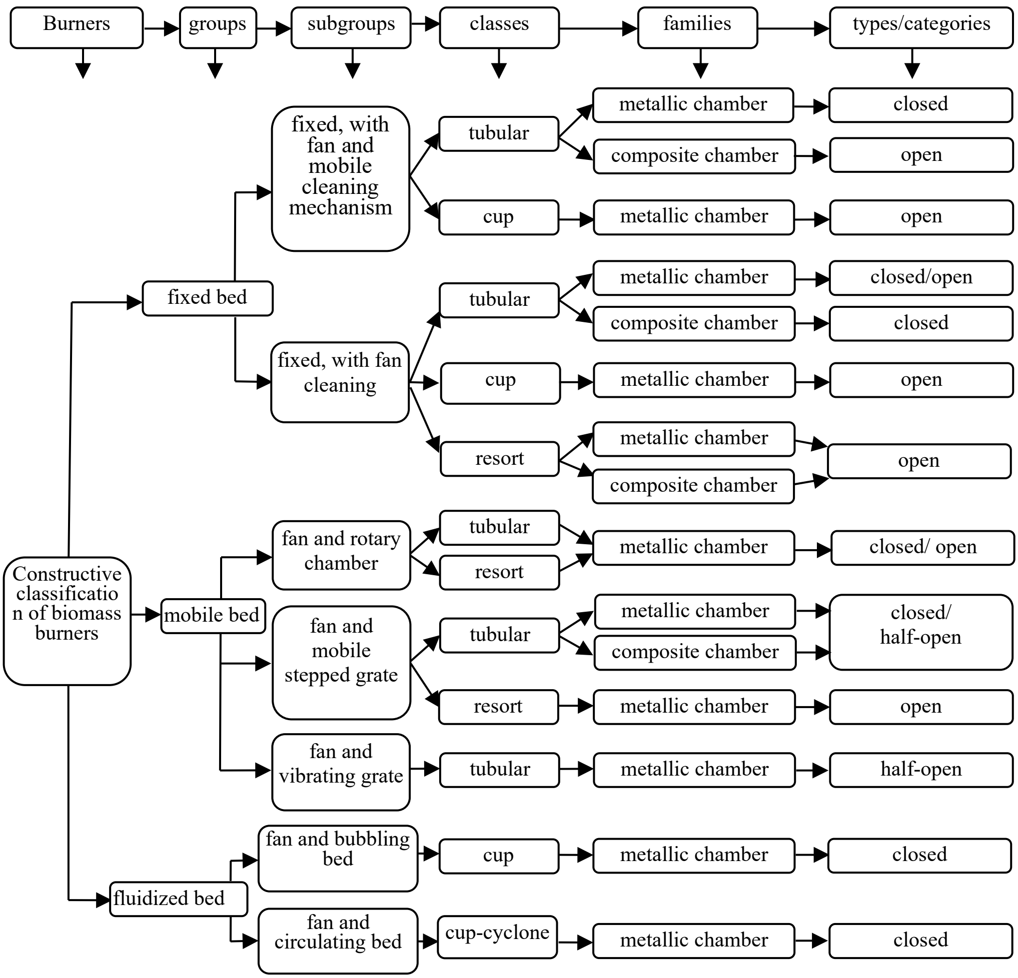

Figure 3. Classification based on constructive criteria of selected BCS

Table 1. The initial analysis matrix of criteria fulfilment in Biomass Combustion Systems

Criteria no./ burner no.	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**	**13**	**14**	**15**	**16**	**17**	**18**	**19**	**20**	**21**	**22**	**23**	**24**	**Sum of met criteria**	**Weight of all fulfilled criteria [%]**
1	0	1	0	0	0	1	1	0	1	1	1	1	1	1	0	1	1	1	0	1	1	0	1	0	15	**62,5**
2	0	0	0	0	0	1	0	0	1	1	0	1	1	1	0	1	1	1	1	1	1	1	1	0	14	**58,3**
3	0	1	0	1	0	1	0	0	1	1	0	1	1	1	0	1	1	0	0	0	1	1	1	0	13	**54,2**
4	0	1	1	0	0	0	0	0	1	1	1	0	0	1	0	0	1	0	1	1	1	0	1	0	11	**45,8**
...	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...	**...**
55	1	0	0	0	1	1	1	0	1	1	0	1	1	1	0	0	1	0	1	1	1	0	1	0	14	**58,3**
56	1	0	0	0	0	1	0	0	1	1	1	1	1	1	0	1	1	0	0	1	1	0	1	0	13	**54,2**
57	1	0	0	1	1	1	0	0	1	1	0	0	0	1	0	1	1	1	1	1	1	0	1	0	14	**58,3**
58	1	0	0	1	1	1	0	1	1	1	0	0	0	1	0	1	1	1	1	1	1	0	1	0	14	**62,5**

The results of establishing of the criteria weight obtained by decision matrix are presented in table 2.

Table 2. Criteria importance: weight decision matrix

Criterion/ criterion	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**	**13**	**14**	**15**	**16**	**17**	**18**	**19**	**20**	**21**	**22**	**23**	**24**	**Row score**	**Criterion weight [%]**
1	1	1	1	0	0	0	1	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	5	1, 6556
2	0	1	1	0	0	0	1	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	4	1, 3245
3	0	0	1	0	0	1	1	1	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	5	1, 6556
4	1	1	1	1	1	1	1	1	0	0	1	1	0	0	1	0	0	0	0	0	0	1	0	0	12	3, 9735
5	1	1	1	0	1	0	1	1	0	0	0	0	0	0	1	0	0	0	0	0	0	1	0	0	8	2, 6490
6	1	1	0	0	1	1	1	1	0	0	0	1	0	0	1	0	0	0	0	0	0	0	0	0	8	2, 6490
7	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0, 3311
8	0	0	0	0	0	0	1	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	2	0, 6623
9	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	0	0	0	1	1	1	1	21	6, 9536
10	1	1	1	1	1	1	1	1	0	1	0	1	1	0	1	0	0	0	0	0	0	1	1	1	15	4, 9669
11	1	1	1	0	1	1	1	1	0	1	1	0	0	0	1	0	1	0	0	0	0	1	1	1	14	4, 6358
12	1	1	1	0	1	0	1	1	0	0	1	1	0	0	1	0	0	0	0	0	0	1	1	0	11	3, 6424
13	1	1	1	1	1	1	1	1	0	0	1	1	1	0	1	0	0	0	0	0	0	1	1	0	14	4, 6358
14	1	1	1	1	1	1	1	1	0	1	1	1	1	1	1	0	0	0	0	0	0	1	1	1	17	5, 6291
15	1	1	1	0	0	0	1	1	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	6	1, 9868
16	1	1	1	1	1	1	1	1	0	1	1	1	1	1	1	1	1	0	0	0	0	1	0	1	18	5, 9603
17	1	1	1	1	1	1	1	1	0	1	0	1	1	1	1	1	1	0	0	0	1	1	1	1	19	6, 2914
18	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	0	1	1	1	1	23	7, 6159
19	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	0	1	0	0	1	1	1	21	6, 9536
20	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	24	7, 9470
21	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	0	1	0	1	1	1	1	22	7, 2848
22	1	1	0	0	0	1	1	1	0	0	0	0	0	0	1	0	0	0	0	0	0	1	0	0	7	2, 3179
23	1	1	1	1	1	1	1	1	0	0	0	0	0	0	1	0	0	0	0	0	0	1	1	0	11	3, 6424
24	1	1	1	1	1	1	1	1	0	0	0	1	1	0	1	0	0	0	0	0	0	1	1	1	14	4, 6358
Column score																									**302**	**100**

Table 3 presents the results of total sum of weight of accomplished criteria for each of 58 selected burners.

Table 3. The optimized analysis matrix of criteria fulfilment in BCS based on criteria weight

Criterion no./ burner no.	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	Weight of BCS, [%]
1	0	1,3	0	0	0	2,6	0,3	0	6,7	5,0	4,6	3,6	4,6	5,6	0	6,0	6,3	7,6	0	7,9	7,3	0	3,6	0	**73,2**
2	0	0	0	0	0	2,6	0	0	6,7	5,0	0	3,6	4,6	5,6	0	6,0	6,3	7,6	7,0	7,9	7,3	2,3	3,6	0	**76,2**
3	0	1,3	0	4,0	0	2,6	0	0	6,7	5,0	0	3,6	4,6	5,6	0	6,0	6,3	0	0	0	7,3	2,3	3,6	0	**59,0**
4	0	1,3	1,7	0	0	0	0	0	6,7	5,0	4,6	0	0	5,6	0	0	6,3	0	7,0	7,9	7,3	0	3,6	0	**57,0**
...	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...
55	1,7	0	0	0	2,6	2,6	0,3	0	6,7	5,0	0	3,6	4,6	5,6	0	0	6,3	0	7,0	7,9	7,3	0	3,6	0	**64,9**
56	1,7	0	0	0	0	2,6	0	0	6,7	5,0	4,6	3,6	4,6	5,6	0	6,0	6,3	0	0	7,9	7,3	0	3,6	0	**65,6**
57	1,7	0	0	4	2,6	2,6	0	0	6,7	5,0	0	0	0	5,6	0	6,0	6,3	7,6	7,0	7,9	7,3	0	3,6	0	**73,85**
58	1,7	0	0	4	2,6	2,6	0	0,7	6,7	5,0	0	0	0	5,6	0	6,0	6,3	7,6	7,0	7,9	7,3	0	3,6	0	**74,5**

For an intuitive analysis were used the overview diagram (chart), with both methods results (Direct Comparison (DC) and Single Value Analysis (SV)). Figure 4 shows the results of the two types of comparison (weight matrix method and simple value analysis method).

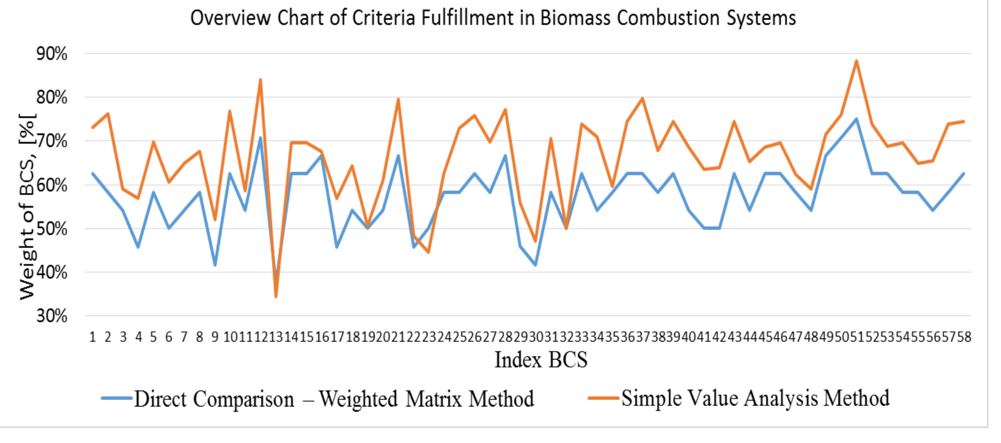

Figure 4. Overview chart of criteria fulfilment in Biomass Combustion Systems

As precised before, according to the authors' knowledge, such analyse was made for the first time, other similarly analysis for BCS were not found, so it was impossible to compare the results. Analysing figure 4, in this situation, it was found no significant differences between both methods (average of relative differences (relative differences=100*|SVi-DCi|/max {SVi;DCi}, from i=1-58) for all 58 BCS is 13%). Another remark is the values obtained by Single Value Analysis method are, usually, greater those obtained by Direct Comparison method. As observed from table 3 and figure 4, the proposed method permits to the manufacturers of semi-automated and automated BCS to evaluate the performance of such equipment by comparison to those available on the market, based on 24 analytical criteria. This approach enables manufacturers to identify the weaknesses of their BCS among the 24 criteria and analyse the areas where improvements can be made, thereby where is possible to enhance both: the performance and market competitiveness. Attention! The method can give useful conclusions if relative differences between DC and SV are less than 15%.

The same two analysis methods can assist researchers in the decision-making process of selecting constructive solutions for the design of new BCS. The methods can be also used to establish an efficient allocation of resources in design and development by adjusting costs according to the weight of the criteria's.

CONCLUSIONS

The analysis of BCS made using proposed hybrid method (both Direct Comparison method and Single Value Analysis method) showed that it could obtain a good possibility for compare simultaneously a lot of constructive and technological solutions with good resolution and significance when, also, a lot of factors are considered. Such analysis is adequate for identifying the optimum solution for a BCS in given technical, economical and investment conditions, based on different criteria. The proposed method could be an initially good selection for future applying of methods for stimulating innovation as TRIZ or others.

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ENZYMATIC PRETREATMENT OF AGRICULTURAL WASTE TO ENHANCE DIGESTIBILITY FOR BIOGAS PRODUCTION

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ABSTRACT

The agricultural sector generates a significant amount of waste and if not properly managed, can represent a real threat to the environment, can pollute terrestrial and aquatic habitats and affect human health. Anaerobic digestion is a promising technology for agricultural waste management that is more sustainable than traditional disposal methods such as incineration and composting. Because of the complex structure of agricultural waste, adequate pre-treatment prior to anaerobic digestion is necessary to increase biodegradability and enhance biogas production. Biological pretreatment is becoming more and more popular due to low toxicity and low energy input compared to chemical and physical pretreatments. In the present paper, pretreatment with bacterial species was applied on agricultural waste consisting of corn stalks, wheat straw and sunflower stalks. Enzyme-producing microorganisms were isolated from soil collected from orchard, solar garden and fertilizer. The tested biomass was first physically pretreated (milling) in order to increase the contact surface area of the particles and thus improve mass transfer. In the second step, the digestibility of macromolecular compounds in the tested substrates was increased by the action of enzymes acting in the inoculated medium with the producing microorganisms. To assess the efficiency of enzyme pretreatment, laboratory tests were carried out to determine the total soluble solids, total solids, pH, weight loss, reducing sugars, and soluble proteins before and after pretreatment of the samples. Microscopic analysis was also performed to observe the particle size of the tested substrate and to determine the number of bacterial cells per milliliter.

Keywords: *microbial enzymes, pretreatment, agricultural waste, digestibility*

INTRODUCTION

Worldwide, waste generation has continued to increase with population growth, urbanization and the effects of economic and industrial progress. The agricultural sector generates a significant amount of waste and if not properly managed, can represent a real threat to the environment, can pollute terrestrial and aquatic habitats and affect human health. The valorization of agricultural waste provides a number of benefits, such as contributes to a clean environment, socio-economic development, resource recovery, and also helps to achieve energy security and circular economy (Awogbemi and Vandi Von Kallon, 2022; Bala et al., 2023). Unlike the linear model, the circular economy focuses on reduce, reuse and recycle activities, minimizing waste and maximizing the use of resources (Sira et al., 2022). In addition, the circular economy model and agricultural waste are related, and both are essential to promoting sustainability in the agricultural sector (Ufitikirezi et al., 2024).

Traditional methods of lignocellulosic waste management, such as grinding and compacting, which reduced management costs but not the impact on the environment, are no longer effective in the context of the circular economy (Blasi et al., 2023).

Anaerobic digestion is a promising technology for agricultural waste management that is more sustainable than traditional disposal methods such as incineration and composting (Mishra et al., 2024). Anaerobic digestion produces methane, which is a clean, sustainable substitute for fossil fuels in power generation, heating, and automobile fuel (Xie et al., 2011). Thus, agricultural residues are a suitable substrate for this transformation due to their abundance and constant availability. Moreover, greenhouse gas emissions such as methane (CH4) and nitrous oxide (N2O) are reduced when agricultural wastes are anaerobically decomposed, and methane is recovered (Alvaro et al., 2024).

The composition of agricultural waste depends on the types of plants, but in general, agricultural waste consists of cellulose, hemicellulose, lignin and pectin. Because of the complex structure of these feedstocks, adequate pre-treatment prior to anaerobic digestion is necessary to increase biodegradability and enhance biogas production (Karthikeyan et al., 2024). Mechanical (physical) and chemical pre-treatments have been shown to have a series of disadvantages, such as: high energy requirements, formation of inhibitory compounds, they are expensive, etc (Schroyen et al., 2014).

Biological pretreatments are becoming more and more popular due to low toxicity and low energy input, being an environmentally friendly method compared to chemical and physical pretreatments. However, one disadvantage is that they tend to be slower in the degradation process (Das et al., 2023). The main biological pretreatment techniques used for lignocellulosic agricultural waste are bacterial pretreatment, enzymatic and fungal pretreatment (Wang et al., 2023; Ferdeș et al., 2020). Biological pretreatment methods using microbial consortia are mainly aimed at breaking down cellulose and hemicellulose. Studies regarding biological pretreatment of lignocellulosic agricultural wastes are also found in the scientific literature. Zhao et al. (Zhao et al., 2020) used in their study mixed enzymes extracted from Trichoderma viride (ETv) and Aspergillus sp. (EAs) for pre-treating maize straw. The authors reported that the optimal enzymes blending ratio was found to be 2:3 (ETv: EAs), and the cumulative methane yield was 31.74% higher than the control.

Weide et al. (2020) studied the effects of five different enzyme mixtures on the increase in the biogas yields of batch anaerobic digestion. The used substrate consisted of grass silage, maize straw, maize silage and the manure of various animals. The results showed that between days 5 and 15 in almost all tests the methane yields was increased of 0.3%–21.1% depending on the substrate. On the other hand, after 60 days of testing, the increase in the total maximum methane yields were in most cases not detectable.

In other research, Sumardiono et al. (Sumardiono et al., 2022) used a combination of physico-chemical pretreatment and physico-biological pretreatment of corn stalks for enhancing biogas production. The physical pretreatment was done by grinding, the NaOH was added for chemical pretreatment and biological pretreatment was done by adding mushroom Phanerochaete chrysosporium (EM-4). After pretreatment, corn stalks and cow manure were mixed in the biodigester with ratio 1:1 for 62 days. The authors reported that the best results were obtained from corn stalks with a size of 20 mesh and the addition of EM-4 7% with a maximum daily biogas yield of 19.86 Lkg-1 on day 28.

Nugraha et al. (Nugraha et al., 2021) tested the effect of pretreatment using amylase and cellulase enzymes on the production of biogas from rice husk waste. The results showed that the highest biogas production was obtained by pretreatment of 18% amylase enzyme, namely 1466 mL, and by pretreatment of 18% cellulase enzyme, namely 1075 mL.

In the present paper, bacterial species were applied on agricultural waste consisting of corn stalks, wheat straw and sunflower stalks. Enzyme-producing microorganisms were isolated from soil collected from orchard, solar garden and fertilizer. The tested biomass was first physically pretreated (milling) in order to increase the contact surface area of the particles and thus improve mass transfer. In the second step, the digestibility degree of macromolecular compounds in the tested substrates was increased by the action of enzymes acting in the inoculated medium with the producing microorganisms. To assess the efficiency of enzyme pretreatment, laboratory tests were carried out to determine the total soluble solids (TSS), total solids (TS), pH, weight loss, reducing sugars and soluble proteins before and after pretreatment of the samples. Microscopic analysis was also performed to observe the particle size of the tested substrate and to determine the number of bacterial cells per milliliter.

MATERIALS AND METHODS

Isolation and selection of enzyme-producing microorganisms

Soil samples were collected from orchard, solar garden and fertilizer which were mixed with sterile water to obtain a suspension of microbial populations. The isolations were carried out in Petri dishes, using the streak technique. For highlighting the cellulolytic, amylolytic, proteolytic, laccase, and lipolytic enzymes produced by the microbial colonies, the culture medium was prepared according to (Dinca et al., 2024) in a previous study. Enzyme indices (I_E) were calculated according to equation 1:

$$I_E = \frac{\text{zone diameter}}{\text{colony diameter}} \quad (1)$$

After the isolation, selection and characterization of 30 possibly producing bacterial colonies, two bacterial species were selected based on enzyme index determination.

Feedstock preparation

The corn stalks (CS), wheat straw (WS) and sunflower stalks (SS) used in this study were collected from Teleorman county, Romania, in summer – autumn 2024. The air-dried feedstocks were first chopped using a Viking GE 150 vegetable waste shredder and then were milled using Fritsch Pulverisette 19, equipped with a sieve with 4 mm square perforation. The milled samples were stored at ambient temperature until use.

Pretreatment with enzyme-producing microorganisms

Five grams of each tested substrate (CS, WS and SS) were mixed with 200 mL of water in a 500 mL Erlenmeyer flask and then autoclaved for 15 min at 121 °C. After flasks cooled at room temperature, the substrate was inoculated with 10 mL of the two types of selected microbial cultures suspension (10^9 cells/mL). All flasks were incubated for 4 days at 25 °C in the orbital incubator Gerhardt Thermoshake (Fig. 1a) under continuous shaking of 150 rpm.

During incubation, each Erlenmeyer flask was covered with a cotton plug in order to reduce humidity loss and to prevent contamination. A control flasks were prepared in the same manner, but only water was added instead of inoculum containing microorganisms. After incubation, the flasks were taken to room temperature, and the mixture was immediately filtrated using a vacuum filtration system, on filter paper with a diameter of 47 mm (Fig. 1b).

a) 

b) 

Figure 1. a) The orbital incubator Gerhardt Thermoshake and **b)** vacuum filtration system used in experiment

Methods of analysis

The evaluation of enzymatic pretreatment on agricultural waste was done by analyzing and interpreting the following parameters: determination of TSS, TS, reduction of substrate mass, pH, reducing sugars and soluble proteins.

For each tested microorganism several variants were performed in parallel: three cultures in Petri dishes for the determination of enzyme indices, respectively three cultures in Erlenmeyer flasks containing different substrates for which the parameters were determined, and the standard deviation was calculated.

The solid fraction was weighed and the mass was compared to initial mass to determine the total solids biodegradation. The content of TSS was measured using an ABBE refractometer and the TS content was determined with a KERN RH 123 – 3 thermobalance. The pH of the liquid samples was determined using a portable pH meter pH 7 Vio.

The concentration of soluble protein was determined by the Lowry method, the absorbance was measured at 660 nm on a T92+PG INSTRUMENTS T92+PG UV-Vis spectrophotometer. The soluble protein concentration (µg mL-1) was determined using the calibration curve plotted for bovine serum albumin (BSA) (Fig. 5a). Sugars concentration was measured using the method in which is used the 3.5-dinitrosalicylic acid (DNS). The absorbances were measured at 540 nm using the T92+ UV VIS spectrophotometer, PG Instruments (Fig. 5b).

Microscopic analyses were done using a Bel Photonics microscope in order to observe the biomass structure before and after biological pretreatment. The bacterial cell count was also determined microscopically using Thoma cell counting chamber.

RESULTS AND DISCUSSION

The two selected bacterial species were named B4 and B6 and were used in the current experiment. Around the producing colonies, the aspect of the culture medium changed due to the diffusion of hydrolytic enzymes acting on the substrate, as can be seen in Table 1 and Figures 2 and 3. Determination of enzyme indices was done for the following enzymes: cellulase, amylase, protease, laccase and lipase.

Table 1. Enzymatic indices of selected species (diameter of hydrolysis zone/ diameter of colony)

Bacterial species	Cellulase index	Amylase index	Protease index	Laccase production	Lipase index
B4	2.2 ± 0.15	3±0.21	5±0.20	positive	0
B6	2.8±0.04	2.9±0.35	3.6±0.34	positive	1.6± 0.13

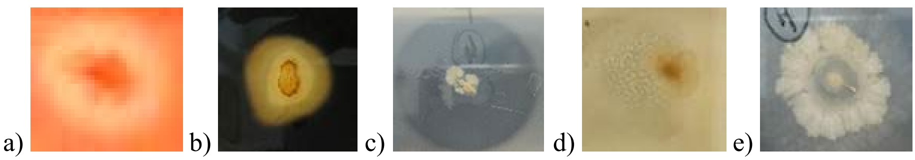


Figure 2. Colonies of bacterial species B4 producing enzymes: **a)** cellulase; **b)** amylase; **c)** protease; **d)** laccase and **e)** lipase

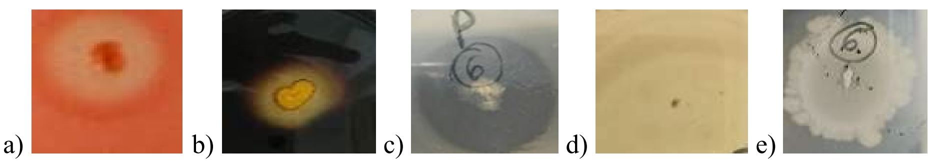


Figure 3. Colonies of bacterial species B6 producing enzymes: **a)** cellulase; **b)** amylase; **c)** protease; **d)** laccase and **e)** lipase

The two bacterial species were grown on nutrient agar in tubes and stored at 4°C until use (Figure 4).

Figure 4. Bacterial species B4 and B6 used in experiment

Figure 5 shows the calibration curves for bovine serum albumin and for reducing sugars.

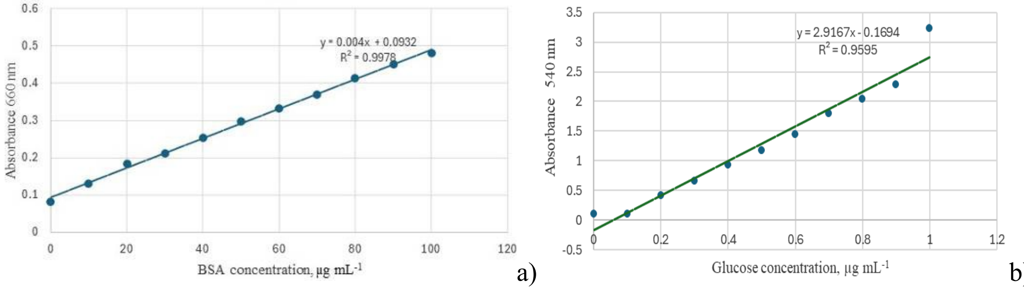


Figure 5. a) BSA calibration curve and **b)** reducing sugars calibration curve

For each variant of tested feedstock were weighed 5 g of substrate with the following values of TS%: CS - 88,27%, WS - 90,73%, and SS - 91,45%.

Table 2. Characteristics of tested feedstocks

Sample	**pH**	**TSS, %**	**Dry weight after 4 days, g**	**Weight loss, g**
CS control	6.94±0.10	1.1± 0.16	3.86±0.32	0.55
CS4	8.65±0.05	1.3±0.10	3.12±0.24	1.29
CS6	8.61±0.03	1.3±0.11	2.94±0.22	1.47
WS control	7.07±0.11	0.8±0.09	4.56±0.24	0.35
WS4	8.16±0.05	0.9±0.08	3.79±0.23	0.74
WS6	7.88±0.03	1.1±0.15	4.28±0.31	0.65
SS control	6.00±0.20	0.9±0.10	3.51±0.34	0.6
SS4	8.56±0.07	1.5±0.12	2.90±0.22	1.67
SS6	8.42±0.05	1.4±0.10	3.60±0.32	0.97

Table 3. Values of sugar and soluble protein concentration in the tested substrate

Sample	Sugar concentration, µg mL^{-1}	Soluble protein concentration, µg mL^{-1}
CS control	0.60±0.042	792±45
CS4	0.67±0.045	840±52
CS6	0.73±0.052	886±56
WS control	0.42±0.031	644±37
WS4	0.51±0.041	739±41
WS6	0.49±0.042	724±40
SS control	0.8±0.061	560±28
SS4	1.1±0.083	592±32
SS6	1.0±0.079	590±30

From the data presented in Table 2, significant differences can be observed between the values of all substrate's characteristics before and after microbial hydrolysis. For all the tested samples (CS, WS and SS), the pH values have increased due to bacteria multiplication in the culture.

For the characteristic TSS%, increases from 0.1 (for WS4) to 0.6 (for SS 4) were observed compared to the corresponding controls. This phenomenon demonstrates that a part of the polymeric substrate has been hydrolysed to soluble compounds with a smaller mass due to the action of bacterial enzymes.

The results presented in the columns for dry weight and weight loss showed the same trend as observed in the column containing TSS % values. In the control samples, the dry weight was always higher which led to lower weight loss values. These values can be explained by a decrease in the mass of macromolecular compounds that solubilize by hydrolysis.

By enzymatic hydrolysis produced by bacterial amylases and cellulases in the culture, the resulting sugar concentration by the DNS analysis method was always higher for samples compared to control (CS, WS and SS) (Table 3). Also, the protein concentration was higher for the bacterial culture samples for the three substrates tested. The results showed that the highest differences of these values (sugar concentration and protein concentration) compared to the control were obtained for CS as substrate, and the lowest for SS (Table 3).

The hydrolytic action of the two bacterial species seems to be similar for all three substrates.

The degradation of the three substrate types (CS, WS and SS) was also visible on the microscope images shown in Figures 6 to 8.

In all images it can be seen that the substrate fragments were larger in size in the control samples than in the samples after enzymatic hydrolysis, which demonstrates that especially amylases, cellulases and lacases acted on starch and lignocellulosic material. Also, in the hydrolysed samples many small fragments with rounded edges were observed. Bacterial growth in cultures containing CS, WS and SS as substrate was analysed by bacterial cell counting with Thoma cell counting chamber. The results are presented in Table 4 and Figure 9 and show that cell counts ranged from 8 x 10^7 cells mL^{-1} to 1.4 x 10^8 cells mL^{-1}.

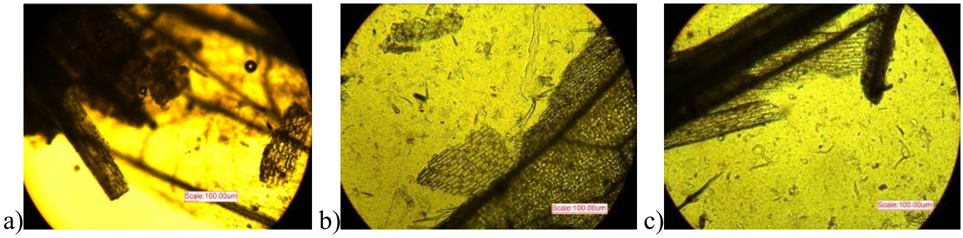


Figure 6. Microscopic images of the CS sample: **a)** untreated; **b)** CS4; **c)** CS 6

Figure 7. Microscopic images of the WS sample: **a)** untreated; **b)** WS4; **c)** WS6

Figure 8. Microscopic images of the SS sample: **a)** untreated; **b)** SS4; **c)** SS6

These values demonstrate that the culture conditions and hydrolysed compounds were optimal for bacterial multiplication. The high number of bacterial cells also has a significant influence on the concentration values of sugars and soluble proteins. Bacteria consume these compounds and therefore the concentration of soluble nutrients is probably lower than if enzymes were used in the absence of bacteria.

Table 4. Number of bacteria/mL culture

No.	Sample	Number of bacteria /mL
1	CS4	1.1×10^8
2	CS6	1.3×10^8
3	WS4	8×10^7
4	WS6	1.2×10^8
5	SS4	1.4×10^8
6	SS6	1.1×10^8

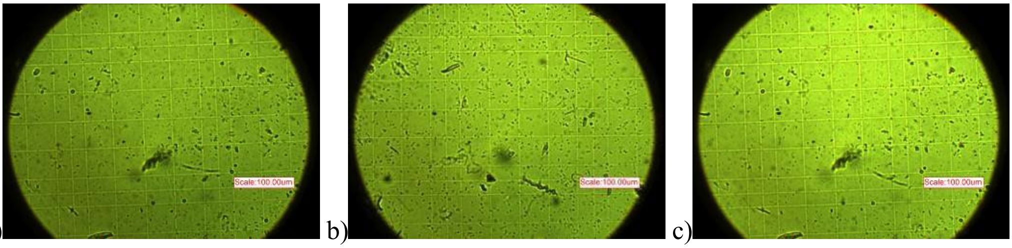
a) b) c)


Figure 9. Number of bacteria per mL: **a)** CS 6; **b)** WS6; **c)** SS4

Recently, similar studies regarding biological pretreatment of lignocellulosic agricultural wastes were conducted by Hossain et al., 2021, Ramarajan and Manohar, 2017 and Zhang et al., 2021.

However, pretreatment of the substrate with high enzyme-degrading microorganisms requires a longer time than physico-chemical pretreatment, but costs can be significantly reduced.

CONCLUSIONS

In the preseny study, two bacterial species, B4 and B6, were selected for pretreatment of some agricultural wastes, namely: corn stalks, wheat straw and sunflower stalks. For all tested substrates, the growth of the two bacterial species for 4 days in submerged culture led to a decrease in the dry weight of the substrate remaining unhydrolyzed simultaneously with an increase in TSS%, sugar concentration and soluble protein concentration. These bacterial species can be used to improve and shorten the hydrolysis phase in the anaerobic digestion process depending on the lignocellulosic substrate used and the process parameters.

Moreover, biological pretreatment with enzyme-producing microorganisms can enhance sugar and protein concentration, and the substrate conversion rate without releasing inhibitory compounds.

The experiments were conducted using microorganisms isolated from garden soil in a non-polluted environment considering that they are part of the normal soil microflora and are therefore non-pathogenic and non-toxic.

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50. ACTUAL TASKS ON AGRICULTURAL ENGINEERING

Original scientific paper

THE POLYMER PROPERTIES OF LIQUEFIED OAK BIOMASS (*QUERCUS ROBUR* L.) AS A POTENTIAL ADDITIVE IN THE PRESSING OF SOLID BIOFUELS

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ABSTRACT

Wood liquefaction is a process in which biomass, such as wood, is chemically converted into a liquid mixture containing valuable organic compounds. Chemicals such as phenol and glycerine are often added to break down the complex wood polymers — lignin, cellulose and hemicellulose — into smaller molecules. The resulting mixture can then be further processed and used as a component of biofuels or chemical raw materials. The aim of the study was to liquefy oak biomass samples with a solvent mixture of glycerol and aqueous phenol solution at different concentrations, using three different solvent-sample ratios (1:3, 1:4 and 1:5) based on parameters from previous scientific studies. After the liquefaction process, the polymer properties of the samples were analyzed, including the liquefaction percentage, insoluble fraction, solid residue and OH number. Based on the results obtained, the optimal liquefaction conditions were determined, allowing for the best polymer properties.

Keywords: *oak, liquefaction, glycerol, phenol, hydroxyl number*

INTRODUCTION

Renewable energy sources play a crucial role in moving away from fossil fuels, tackling climate change, reducing pollution and improving energy security. Solar, geothermal and wind energy, hydropower and biomass offer sustainable alternatives that can meet the world's energy needs with minimal environmental impact (Osman et al., 2023). Biomass is a renewable energy source derived from organic materials such as wood, agricultural residues and waste. As a sustainable alternative to fossil fuels, biomass contributes to reducing greenhouse gas emissions when managed responsibly. However, its environmental impact depends on factors such as sourcing, production methods and land use practices. When used efficiently, biomass can play a key role in meeting energy needs while supporting the transition to a low-carbon, sustainable future (Usman et al., 2022). As a carbon-neutral alternative to fossil fuels, wood contributes to reducing greenhouse gas emissions and is therefore an environmentally friendly resource. By-products of wood processing such as wood chips, pellets and sawdust further increase the efficiency of wood biomass and make it a key factor in the transition to sustainable energy (Thiffault et al., 2023).

In Croatia, the total area of forests and woodlands is 2.759.039 ha, which accounts for 49.3% of the country's land area. Deciduous forests, especially oak and beech, are the most widespread, while coniferous forests, such as spruce and fir, are more common in the mountainous regions (Hrvatske šume, 2024).

Wood is a three-dimensional biopolymer composite consisting of an interconnected network of cellulose, lignin and hemicellulose as well as small amounts of extractives and inorganic substances. The cell walls of wood consist mainly of carbohydrates (65-75%) in combination with lignin. Dry wood has an elemental composition of about 50% carbon, 6% hydrogen, 44% oxygen and traces of inorganic components. Simple chemical analyses can be used to distinguish between hardwood and softwood, but these methods are not precise enough to identify individual tree species, as there are significant differences within each species and similarities between different species (Rowell et al., 2005). The cellulose content is around 40% in both hardwood and softwood, the lignin content is 25-30% in softwood and 20-25% in hardwood, while the hemicellulose content is 25-30% in softwood and 30-35% in hardwood. Other components, mainly extractives, usually make up about 5% of the wood content (Pettersen, 1984; Antonović, 2007; Río Andrade et al., 2013). Miscanthus, for example, contains around 49% cellulose, 29% lignin and 19% hemicelluloses (Bilandžija et al. 2017).

The use of wood for liquefaction has become increasingly important due to the growing demand for renewable energy sources and sustainable materials. Processes such as pyrolysis, hydrothermal treatment and catalytic processing enable the conversion of wood biomass into liquid fuels such as bio-oil or chemicals for further industrial use. Although the cost and technical complexity of these processes remain a challenge, advances in wood liquefaction technology promise to make a significant contribution to a sustainable economy (Öcal and Yüksel, 2023). In this process, the wood is generally exposed to high temperatures (250-500 °C) and high pressure (5-20 MPa), using solvents such as phenol, glycerol or alcohols. This treatment breaks down the polymeric components of the wood and converts them into smaller molecules, creating a liquid product that can be further processed into fuels, chemicals and resins, providing a renewable alternative to petroleum-based products (Lak et al., 2023).

There are two main methods for liquefying wood: direct liquefaction, in which the wood is converted directly into bio-oil using solvents and heat, and indirect liquefaction, in which the wood is first gasified to produce synthetic gas (a mixture of carbon monoxide and hydrogen), which is then converted into liquid hydrocarbons through processes such as Fischer-Tropsch synthesis. Depending on the solvent, liquefaction can be divided into: Liquefaction with polyhydric alcohols (ethylene glycol, glycerol, diethylene glycol, polyethylene glycol, dipropylene glycol), and liquefaction with phenols (Bhaskar et al., 2011).

The main objective of the research was to determine the effect of adding an aqueous phenol solution mixed with glycerol on the polymer properties of liquefied oak wood (*Quercus robur* L.) at different concentrations (5-50%) using acidic catalysts under well-defined conditions. Based on the results obtained, the most favorable liquefaction conditions were determined to achieve optimal polymer properties, which represent the first step towards the development of applications for this material in various bioproducts such as pellets.

MATERIALS AND METHODS

In this research, oak biomass (*Quercus robur* L.*)* originated from the Spačva forest area in Vukovar-Srijem County, while the samples themselves were collected in the wood-processing company Bjelin d.o.o., Otok.

Sampling was carried out according to test method T257 (TAPPI). The samples were taken immediately after felling the trees, air-dried at room temperature for two weeks, debarked and a mixture of sapwood and heartwood was used for the analysis. The samples were ground using an SM400 cutting mill (RetschGmbH, Haan, Germany) with a 10.0 mm round hole sieve (HRN EN ISO 14780:2017). Further grinding was carried out using an SR300 hammer mill (RetschGmbH, Haan, Germany) with a sieve with a 1.0 mm trapezoidal hole (HRN EN ISO 14780:2017). After grinding, the samples were sieved using an AS200 BASIC shaker (RetschGmbH, Haan, Germany) (HRN EN ISO 17827-2:2024), which contained sieves with different mesh sizes (ISO 3310-1:2016). After grinding and sieving, particles with a size between 0.50 and 1.00 mm were selected for further analysis, as previous studies recommended this size range as ideal for isolating the chemical composition. All chemical analyses and liquefaction procedures were performed in triplicate to ensure the reliability of the results.

The analyses of moisture and ash content as well as lignocellulosic composition of oak biomass (extractives, cellulose, lignin and hemicellulose) were performed according to standard methods and based on previous studies (Antonović et al., 2019; Jovičić et al., 2022; Matin et al., 2024). The moisture content (HRN EN ISO 18134-2:2024) was determined using a Memmert UF160 laboratory dryer (Memmert GmbH + Co.KG, Schwabach, Germany), while the ash content (HRN EN ISO 18122:2022) was measured in a Nabertherm L9/11/B170 muffle furnace (Nabertherm GmbH, Lilienthal, Germany). The content of extractants (TAPPI T 204) was determined by solvent reaction with methanol (CH_3OH) and benzene (C_6H_6) in a volume ratio of 1:1 using a Soxhlet R108S BEHRotest extractor (Labor-Technik-GmbH, Düsseldorf, Germany). The cellulose content was analysed by treating the sample with a solution of nitric acid (HNO_3) and ethanol (C_2H_5OH) in a volume ratio of 1:4 and subsequent boiling in a Hydro H9V Lauda water bath (Lauda GmbH, Lauda-Königshofen, Germany). The lignin content was measured by reacting the sample with 72 % sulphuric acid (H_2SO_4) (TAPPI T 222) and boiling on an IKA C-MAG HS7 magnetic stirrer (IKA®-Werke GmbH & Co.KG, Staufen, Germany), while the hemicellulose content was calculated (HC=100-(%P+%AT+%C+%L)).

Ground and sieved oak biomass samples (0.5 to 1.00 mm) were used for liquefaction. Glycerol was used as the liquefying reagent, to which an 8% phenol solution in distilled water was added in varying ratios (5-50%). At the beginning of the process, 100 g glycerol, 3 g sulfuric acid (as catalyst) and the indicated amount of an 8% phenol solution were combined in a 500 mL flask with a stir bar. The flask was placed on a heated magnetic stirrer with an attached cooler. The solvent was heated to 150 °C and the wood sample (20-33 g, depending on the sample to solvent ratio of 1:3, 1:4 or 1:5) was added. Liquefaction was continued at 150 °C for 120 minutes while the temperature was closely monitored. After completion of the liquefaction process, the liquefied samples were transferred to plastic beakers for further analysis. The analyzes of the polymer properties (insoluble residue, liquefaction percentage, dry matter and OH number) were performed according to standard methods and based on previous studies (Antonović et al., 2019; Jovičić et al., 2022; Matin et al., 2024). The insoluble residue (IR) of liquefied wood refers to the biomass fraction that remains undissolved during the liquefaction process and remains as a solid residue. The liquefied oak samples were dissolved in a mixture of 1,4-dioxane and water (8/2), stirred for 60 minutes and filtered through a B2 glass fiber filter. The solution was washed until it was colorless, and the dioxane-insoluble product was dried at 105 °C to constant weight. The mass of the insoluble residue was measured to calculate its percentage of the initial mass of the sample according to the following formula:

$$IR = \frac{[m(fp+ds)-m(fp)]}{m(s)}\ x\ 100 \quad (\%) \tag{1}$$

where: m(fp+ds) – mass of the filter paper and dry sample, m(fp) – mass of the filter paper, m(s) – mass of the sample.

The percentage of liquefaction (LP) is a measure that describes the amount of biomass that is converted into a liquid form during the liquefaction process. A sample of 1 g of liquefied material is weighed into a dry beaker, followed by 100 mL of distilled water and a magnetic stirrer. The beaker is stirred with a magnetic stirrer for 30 minutes, while the mass of the filter paper is measured. After stirring, the sample is filtered through the paper in a glass funnel into an Erlenmeyer flask. The undissolved portion remains on the paper, while the liquid collects in the flask. The filter paper is then dried for 24 hours at 80°C ± 2°C until a constant weight is achieved. The percentage of liquefaction is then calculated using the following formula:

$$LP = 100 - IR \quad (\%) \tag{2}$$

The dry matter (DM) of liquefied wood refers to the amount of solid material present in the liquid product after the thermochemical liquefaction process of wood biomass. The percentage of DM was determined by weighing an empty watch glass and a 1 g sample. The samples were then dried in a drying oven at a temperature of 150±2 °C for 24 hours, cooled in a desiccator and then weighed again together with the watch glass. The percentage of DM was determined using the following formula:

$$DM = \frac{[m(wg+ds)-m(wg)]}{m(s)}\ x\ 100 \quad (\%) \tag{3}$$

where: m(wg+ds) – mass of the watch glass and dry sample, m(wg) – mass of the watch glass, m(s) – mass of the sample.

The hydroxyl number (OH) indicates the amount of potassium hydroxide (KOH) in milligrams required to neutralize the hydroxyl groups in one gram of a sample, expressed in mg KOH/g. For biomass and biofuels, it is crucial for assessing the reactivity of materials in processes such as polymer, adhesive and resin production. A high OH value indicates that more reactive hydroxyl groups are present, which are important for polymerization (Antonović et al., 2019). To determine OH, 0.51 to 0.56 g of the sample was added to a beaker containing 25 mL of esterification reagent. The beaker was heated in a water bath at 98±2°C for 15 minutes. After cooling, 50 mL of pyridine and 10 mL of hot distilled water were added and the sample was mixed with a magnetic stirrer and a pH meter. The sample was titrated to the equivalence point with a 0.5 M potassium hydroxide solution. The OH was determined using the formula:

$$OH = \frac{(B-A) \times N \times 56{,}1}{m} \, x \, 100 \qquad (\%) \qquad (4)$$

where: B – consumption of KOH (g), A – consumption of KOH for the blank test, N – molarity of the solution, m – mass of the sample.

RESULTS AND DISCUSSION

Based on the methods used and the tests carried out on oak biomass and liquefied samples, the following results were obtained.

Table 1. Chemical group composition of the biomass of oak wood (%)

	Sample			Mean
	1	2	3	
Moisture	6.76	6.93	6.88	6.86
Ash	0.29	0.28	0.30	0.29
Extractives	7.69	7.81	7.72	7.74
Celullose	49.11	49.01	49.20	49.11
Lignin	29.48	29.39	29.42	29.43
Hemicellulose	14.86	15.05	14.93	14.95

Moisture in the biomass lowers the energy density and can hinder the liquefaction process, which reduces the yield and quality of the bio-oil. Controlling moisture is critical for optimal process efficiency. Table 1 shows that all three oak samples had almost the same value. Ash content is an important indicator of the mineral components of biomass that do not contribute to heat production when biomass is evaluated for energy production. The mean value of the ash content of the three oak samples in this study was 0.29%, which is consistent with the literature, as Voicea et al. (2013) reported 0.51% and Donata et al. (2010) reported 0.30%. The lignocellulosic composition of oak generally comprises three main components: Cellulose, hemicellulose and lignin. These values may vary slightly depending on factors such as the specific oak species and growing conditions. The lignocellulosic composition of oak wood does not deviate from the literature data, in which Donata et al. (2010) found 46.3 to 48.1% cellulose, 26.5 to 27.1% lignin and 3.8 to 4.2% extractives; Antonović et al. (2019) state 47.23% cellulose and 21.82% lignin, while Öcal and Yüksel (2023) state 41.0% cellulose, 23.7% hemicellulose, 28.3% lignin and 7.0% extractives.

To evaluate the results of liquefaction of oak biomass with an 8% phenol solution in distilled water, a control samples were prepared. In this control, the oak biomass was liquefied in three different ratios with glycerol and sulphuric acid only (Table 2).

Table 2. Polymer properties of the liquefied samples (100% glycerol)

Ratio	Polymer properties			
	LP (%)	**IR (%)**	**DM (%)**	**OH (mg KOH/g)**
1:3	83.29	16.71	56.88	644.12
1:4	88.54	11.46	53.11	753.88
1:5	91.47	8.53	50.09	836.31

The polymer properties of the liquefied oak samples are listed in Tables 3, 4 and 5, where a mixture of glycerol and 8% aqueous phenol solution (liquefaction ratio 1:3, 1:4 and 1:5) was used as solvent.

Table 3. Polymer properties of liquefied samples with a liquefaction ratio of 1:3

8% solution of phenol in H_2O	Polymer properties (1:3)			
	LP (%)	**IR (%)**	**DM (%)**	**OH (mg KOH/g)**
5%	86.11	13.89	54.15	741.55
10%	90.22	9.78	49.38	824.37
15%	88.21	11.79	48.54	761.21
20%	88.43	11.57	46.12	765.34
25%	88.81	11.19	43.32	775.79
30%	89.29	10.71	45.77	788.41
35%	89.09	11.91	42.65	786.18
40%	87.89	12.11	40.05	742.05
45%	88.05	11.95	41.16	758.89
50%	87.81	12.19	39.33	742.74
Mean	**88.16**	**11.94**	**45.04**	**768.65**

The results of the 1:3 liquefaction show that the best percentage of liquefaction between 88.43 and 90.22% was achieved by adding 20 to 35% of an 8% aqueous phenol solution to glycerol. These percentages also gave the highest values of OH numbers, which were between 765.34 and 824.37 mg KOH/g. Table 4 shows that at a liquefaction ratio of 1:4, the best liquefaction percentage was achieved by adding 25 to 50% of an 8% aqueous phenol solution to glycerol and was between 90.12 and 91.42%; correspondingly, the highest OH numbers of 829.62 to 869.95 mg KOH/g were obtained. From the liquefaction results of the 1:5 ratio (Table 5), the best liquefaction percentage of 92.38 to 92.85 % was obtained by adding 25 to 50% of an 8% aqueous phenol solution to glycerol. However, looking at all the results of liquefaction at 1:5 ratio, it can be seen that there are almost no big differences and all gave high values of OH number, so that the highest value was 877.32 mg KOH/g.

Table 4. Polymer properties of liquefied samples with a liquefaction ratio of 1:4

8% solution of phenol in H_2O	Polymer properties (1:4)			
	LP (%)	IR (%)	DM (%)	OH (mg KOH/g)
5%	88.21	11.79	52.89	795.66
10%	88.89	11.11	48.45	783.36
15%	89.34	10.66	45.85	797.92
20%	90.12	9.88	45.92	818.88
25%	90.75	9.25	42.99	829.62
30%	90.91	9.09	41.53	835.81
35%	90.54	9.46	38.29	823.42
40%	90.35	9.65	39.48	823.91
45%	91.05	8.95	38.99	847.66
50%	91.42	9.58	38.62	869.95
Mean	**90.16**	**9.94**	**43.30**	**822.62**

Compared to previous studies, the LP of oak samples in this study ranged from 59.0 to 97.0% as reported by Gosz et al. (2021) and 91.98% as found by Antonović et al. (2019). In comparison, the percentage of liquefaction for twelve hardwood species ranged from 68.9 to 93.0% at liquefaction ratios of 1:1 to 1:3 (Kumar et al., 2018), while it ranged from 69.8 to 82.6% for corn stalk liquefaction, as found by Mathanker et al. (2020).

Table 5. Polymer properties of liquefied samples with a liquefaction ratio of 1:5

8% solution of phenol in H_2O	Polymer properties (1:5)			
	LP (%)	IR (%)	DM (%)	OH (mg KOH/g)
5%	90.61	9.39	49.59	823.44
10%	91.38	8.62	46.01	865.61
15%	90.68	9.32	45.62	824.72
20%	91.24	8.76	43.68	860.11
25%	92.38	7.62	40.13	871.82
30%	92.85	7.15	39.51	877.32
35%	92.27	7.73	38.58	868.21
40%	91.98	8.02	38.05	864.63
45%	92.51	7.49	35.77	872.52
50%	92.76	7.24	35.85	875.68
Mean	**91.87**	**8.13**	**41.28**	**860.41**

The highest percentage of IR was found in this study at a ratio of 1:3 and amounted to 12.19%, which is higher than the value of 8.02 reported for oak by Antonović et al. (2019). The lowest value of OH in the liquefied oak samples was found at a ratio of 1:3 with 741.55 mg KOH/g, while the highest value of almost 880 mg KOH/g was measured at a ratio of 1:5. A comparison with the literature shows that the OH value for oak is consistent with the reported values, where Antonović et al. (2019) give an OH value of 744 mg KOH/g f, Gosz et al. (2021) give a range of 114–813 mg KOH/g, while Matin et al. (2024) give a range of 492.12-839.01 mg KOH/g. For other materials, Đurović et al. (2024) found values between 569and 836 mg KOH/g for hemp and 429 and 612 mg KOH/g for soybeans, in each case at liquefaction ratios of 1:3–1:5.

CONCLUSIONS

The liquefaction of oak biomass samples was carried out under precisely defined conditions in three different ratios with a solvent mixture of polyhydric alcohol glycerol, 8% aqueous phenol solution in ten different percentages (5-50%) and the addition of 3% sulphuric acid. Based on the results obtained, it can be concluded that the best liquefaction results, considering the liquefaction percentage as well as the OH number values, were obtained at a liquefaction ratio of 1:5 with an addition of 25-50% of an 8% aqueous phenol solution, which led to a better liquefaction of the oak biomass in the solvent itself. The OH number as the most important parameter of liquefaction, with regard to the further use of the liquefied samples, showed the highest values at a liquefaction ratio of 1:5 with values up to almost 880 mg KOH/g, but also the ratio of 1:4 should not be disregarded, which resulted in slightly weaker, but still equally high values. If the results of the control liquefaction (100 % glycerol) are compared with the liquefaction in which ten different percentages of an 8 % water-phenol solution were added, it can be seen that there was an improvement in the liquefaction results for all ratios of phenolic liquefaction. At all ratios, a higher liquefaction percentage, a lower proportion of insoluble residues and dry matter and higher OH values were achieved.

This study offers new considerations on the possibilities of utilising and applying liquefied biomass from alder wood by adding an aqueous phenol solution to glycerol. It can serve as a reference for the further development of environmentally friendly products such as pellets, as research has shown that the addition of liquefied wood in different percentages can improve both the energy value and the qualitative properties of pellets, such as mechanical hardness.

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50. ACTUAL TASKS ON AGRICULTURAL ENGINEERING

Original scientific paper

ENERGETIC WILLOW SLOW PYROLYSIS: EFFECT OF TEMPERATURE AND HEATING RATE

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ABSTRACT

This paper presents the thermal analysis of the slow pyrolysis process for Energetic Willow, in order to identify the main transformation stages that occur during the pyrolysis process, which converts the biomass into valuable resources for energy production: biochar, bio-oil and Syngas. In order to be able to carry out and estimate the biochar production in a pyrolysis pilot station, a quantitative analysis of pyrolyzed Willow biochar has been processed under different conditions. Energetic Willow biomass from a three-year plantation was subjected to pyrolysis within temperature range from 400 to 800 °C. Following 7 experiments, the results of the biochar production analysis, were mathematically modelled using the multiple regression, to obtain a relation that can predict the biochar production from pyrolysis of Energetic Willow. The achieved product yield can vary significantly according to the slow pyrolysis parameters. By comparing the significance threshold of the heating rate and temperature parameters, we can see that the temperature used in the pyrolysis process has a significant impact on biochar production compared to the heating rate parameter. The mathematical model resulting from the experimental analysis and the statistical processing and testing of the obtained results allows estimation of the percentage of biochar produced under present conditions, optimizing the industrial pyrolysis processes of Energetic willow by using ideal temperatures and heating rates in order to to maximize process efficiency, lower energy consumption and shorter process time.

Keywords: *biochar, Energetic Willow, slow pyrolysis, process parameters.*

INTRODUCTION

The benefits of Energetic Willow (Salix Viminalis) as a source of biomass energy and by-products are numerous as it can be grown on floodplains and can be used in sewage treatment areas in domestic sewage treatment sections (Tucu and Hollerbach, 2011; Tucu and Filipovici, 2014; Tucu, 2014). It has a very good water evaporation capacity and growth, absorbing most of the biological substances - impurities in wastewater. Various thermal processes, including low-temperature pyrolysis, are used to improve the energy potential with supply of energy to the process and its recovery in form of heat or products such as biochar gas, or oil. Biochar is a important element in many industries and biorefinery configurations that can serve as a primary or co-product. That is projected to have large markets for soil amendment, carbon storage, adsorption, and biomaterials, among other uses, including environmental engineering (Sygula et al., 2021). Over the past years, there has been a growing utilization of biomass derived from agricultural crops, industrial waste, and wood industry waste as a fuel source in the energy industry (Unyay H et al., 2023). Producing biochar from lignocellulosic biomass, from agricultural crops, forest and agricultural wastes represents an excellent way to valorize into bio-based materials (Ferraro et al.,2021; Abdelhafez, 2017).

MATERIAL AND METHODS

Materials

The analyzed material from the present study is Energetic Willow (Salix Viminalis var. Energo). It is a fast-growing plant, 3 cm / day, at maturity reaches a height of 6-7 meters, having a diameter of up to 3-4 cm. The stems of the Energetic Willow were taken to the laboratory and kept at ambient temperature for 30 days for drying. After this step, the samples were grinded at 3-5 mm diameter, to form a homogeneous structure of the raw material for the slow pyrolysis process. Table 1 presents a characterisation of the biomass prior to pyrolysis, resulted after the proximate analysis (Filipovici et al., 2016).

Table 1. Results of the proximate analysis for Willow

Composition	Value, (% dry basis)
Moisture	8.91
Fixed carbon content	19.80
Volatile	67.32
Ash	3.96

Pyrolysis Equipment

The experimental stage of slow pyrolysis was carried out using an experimental stand, employing an electrically heated fixed bed reactor, used for thermogravimetric analysis, enabled to precisely set the required heating rate and the final temperature of the process. The experimental Equipment was described in previous papers (Filipovici et al., 2017; Filipovici and Tucu, 2014).

Experimental Methodology

The experimental methodology was based principally on thermal analysis under conditions specific to the slow pyrolysis process, according to specific research algorithm (figure 1). Changes in physical and chemical nature of the sample in relation to the programmed temperature and total process time were studied by means of a thermal analysis. In the present study, 7 pyrolysis thermal analysis experiments for the Energetic Willow were performed. The materials were initially dried in oven, 24 h at 105°C. In the experimental procedure, two types of experiments were used to determine the influence of temperature and the influence of the heating rate in the thermal decomposition process:

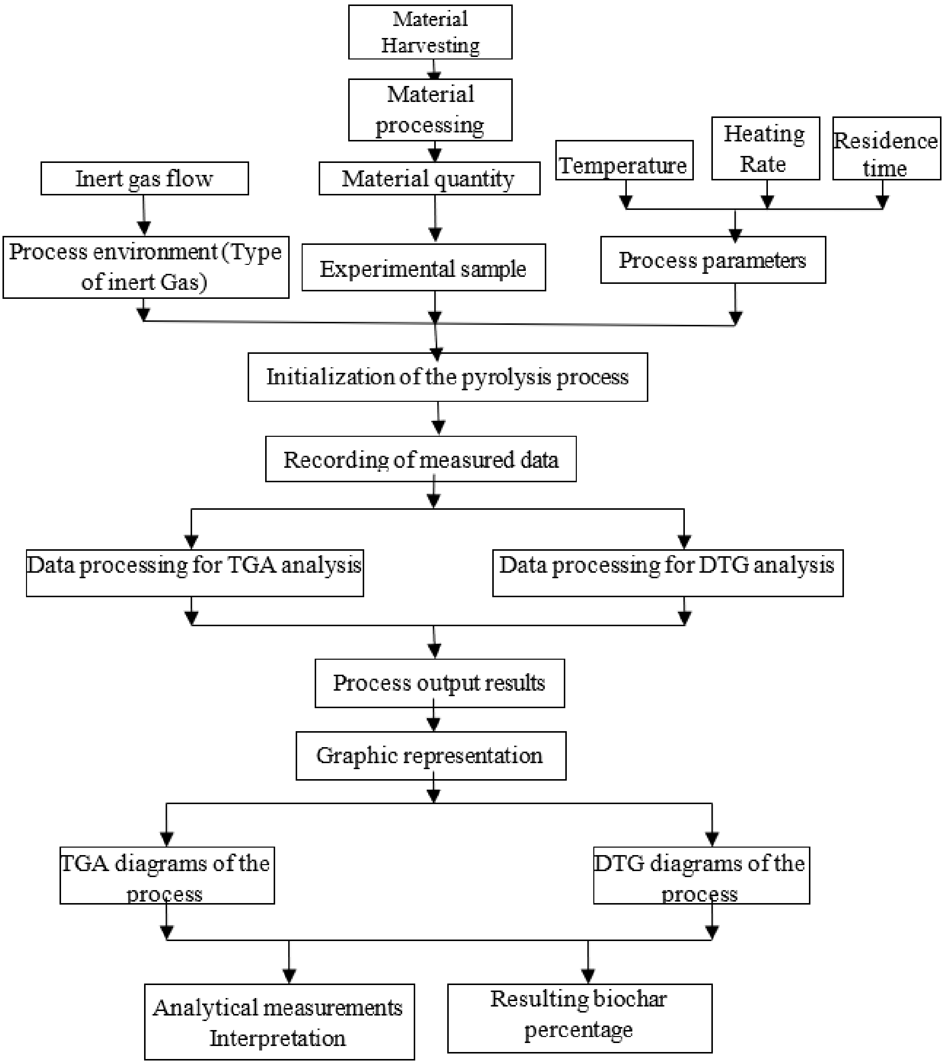

Figure1. Research methodology for slow pyrolysis process

For the determination of the temperature influence, a sample of 1.2 g of biomass was used in each experiment (three times samples replicated). The sample was introduced into the reactor and subjected to a heating process at final temperatures of 400 °C, 500 °C, 600 °C, and 800 °C, for each experiment. The heating rate for each experiment was 10 °C · min^{-1}. After the set temperature has been reached in the reactor, the material sample was kept under the same environmental conditions (inert) for 5 minutes;

For the determination of the influence of the heating rate, a sample of 1.2 g of biomass was used in each experiment (three times samples replicated), which was introduced into the reactor and subjected to a heat treatment at the final temperature of 800 °C, heating rate of 10 ° C·min-1, 20 ° C·min-1, 40 ° C·min-1 and 65 ° C·min-1, for each experiment. After the set temperature has been reached in the reactor, the material sample was kept under the same environmental conditions (inert) for 5 minutes. The mass of the sample m and the temperature t in the centre of the reactor were recorded during the experiment as time dependent variables.

Within the reactor, an inert CO2 environment was provided to overpressure against atmospheric pressure. For each experiment, a constant flow rate of 80 ml·min-1 CO2 was maintained. Multiple regression has been used to determine the dependency relationships between the biochar percent (X)-dependable variable and the two independent variables of the pyrolysis process: final temperature of the process (Xt) and heating rate (Xv). Analytical tools in the form of multivariate ANOVA were used for the statistical analysis of the experimental test results. The method allows us to identify the factors that have a statistically significant influence on the tested parameter.

RESULTS AND DISCUSSION

The Graphic representation results of the pyrolysis process for the Energetic Willow (Salix) are revealed in figures 2 and 3 (because the resulted values were not significant different (1%), the represented values were the average of each three samples).

During the pyrolysis of energetic willow, the time analysis transformations were identified: The main stages that occur of the specific pyrolysis process, which converts the biomass into biofuels. The first loss of mass occurs by removing H_2O from the raw material and constitutes the drying step. Drying usually occurs at temperatures below 120 °C when the heating rate of the material is 10-20 °C·min^{-1}, and in the case of higher heating rates, it is possible to reach a temperature up to values 220 °C. In the second step, the mass of the pyrolyzed matter continues to decrease, due to specific reactions that occur by reflux and depolymerization, resulting in compounds such as CO, CO_2, formic, hexadecanoic acid, or others extraction components (Roman K. et al., 2021). In the experiments, for heating rates 10 °C·min^{-1}, the torrefaction occurred in the temperature range of 110 °C to 330 °C and for heating rates of 20 °C·min^{-1}, the reaction appeared sporadically up to 420 °C. If higher heating rates are used, the reaction can go up to temperatures around 600 °C.

In the third stage of the pyrolysis process, the devolatilization of the material takes place, a process involving specific endothermic reactions, resulting in CO, CO_2, benzene, butanediol, phenol tar and other organic components (Roman K. et al., 2021). At this stage, the highest conversion rate of the raw material is recorded, the process is carried out in a short time, under the conditions of achieving the highest rate of decomposition in the process.

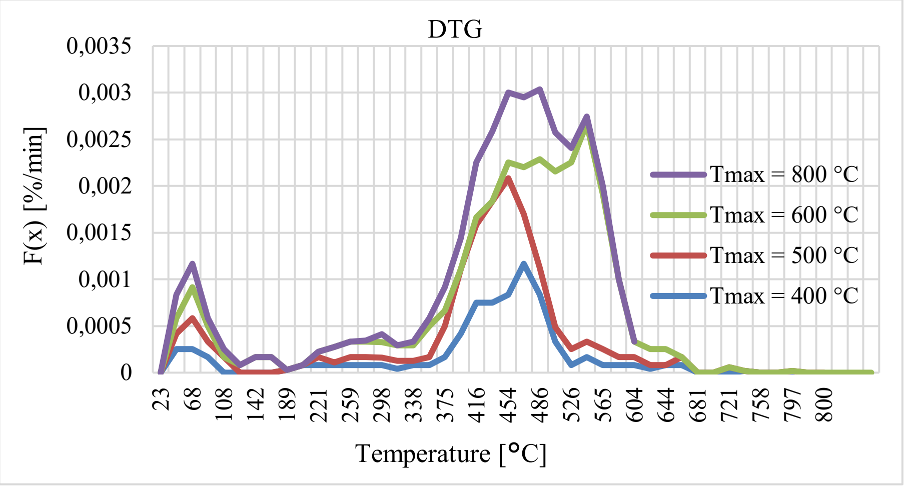

Figure 2. Salix rate decomposition during pyrolysis at different temperatures

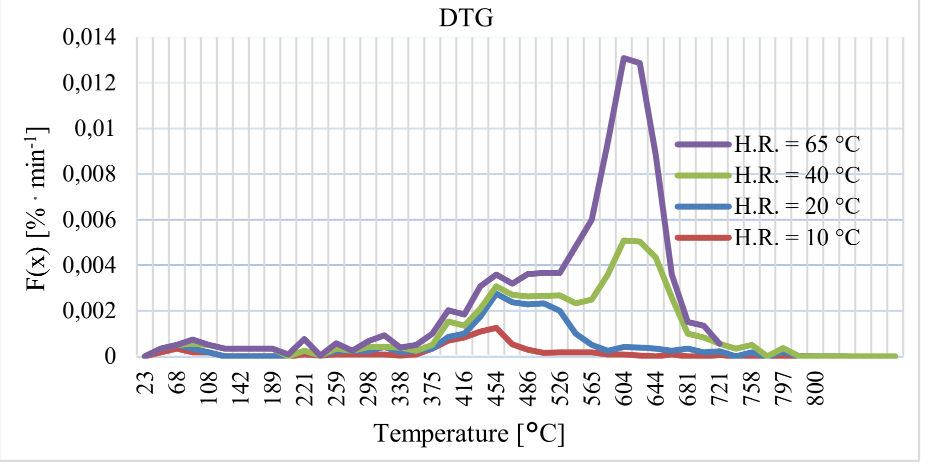

Figure 3. Salix rate decomposition during pyrolysis at different heating rates

During performed experiments, the following were observed:

- - when the temperature of 400 °C is reached, there is no complete devolatilization, it is necessary to keep it in the isothermal temperature stage;
- - for heating rate 10 °C, min^{-1}, decomposition of volatile matter occurred at temperatures up to 500 °C.
- - for higher heating rates, complete devolatilization was around 600 °C for a heating rate of 20 °C·min^{-1} and 700 °C for 40 °C·min^{-1} and 800 °C for heating rate of 65 °C·min^{-1}.

In the fourth stage there was a decrease in mass, due to carbonization and gasification processes. For experiments performed at heating rates of 10 °C · min^{-1} and 400 ºC, this step does not occur. Experiments with heating temperatures of 500 ºC and 600 ºC lead to carbonization, and gasification occurs at temperatures above 700 ºC, which will reduce the percentage of the obtained char. As with the other stages, an increase in the heating rate will cause higher temperatures to reach the last stage, above 700 °C.

Table 2. Thermal analysis of the slow pyrolysis process for Energetic Willow (Salix)

Exp.	Final temp.	Process duration	H. Rate	Drying	Torrefaction	Devolatilization	Carbonization, Gazeification	Char
	[°C]	[min]	[°C/min]	[°C]	[°C]	[°C]	[°C]	[%]
1	400	60	10	0-121	121-306	306-400	Does not occur	40.88
2	500	70	10	0-121	121-306	306-500	Carbonization	30.00
3	600	80	10	0-121	121-306	306-523	523-600	23.73
4	800	85	10	0-121	121-306	306-523	523-800	22.5
5	800	45	20	0-121	121-375	375-584	584-800	21.66
6	800	24	40	0-201	201-401	401-718	718-800	20.66
7	800	12	65	0-164	264-539	539-800	800	19.84

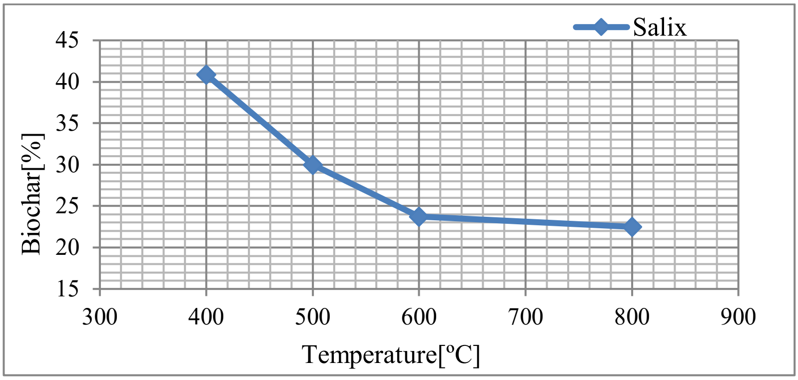

Figure 4. Experimental data at different temperatures

Slow pyrolysis process modelling for quantitative estimation of char production

In order to be able to carry out estimating of char production in the future, a quantitative analysis of pyrolyzed char has been proposed under different process conditions.

Following the 7 experiments, the results of the biochar production analysis (presented in figures 8 and 9), were mathematically modelled using the multiple regression, to obtain a relation that can predict the biochar production from industrial pyrolysis of biomass raw materials.

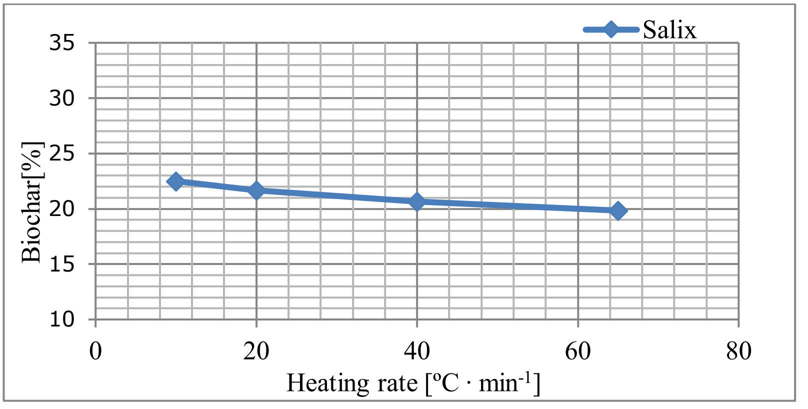

Figure 5. Experimental data at different heating rates

The value of α was taken into account, characterizing the level of significance, was assumed to be 0.05, which is the difference between unity and the confidence coefficient F =0.95 (F = 1- α).

Table 2 and table 3 present the results of multiple regression, in order to determine de statistical relevance of the temperature and heating rate influence, on biochar production.

Table 2. Regression statistics parameters for Energetic Willow (Salix)

Multiple R	0.917365997
R Square	0.841560372
Adjusted R Square	0.762340558
Standard Error	3.656605732
Observations	7

Table 3. ANOVA and Coefficents Statistics for Energetic Willow (Salix)

	df	**SS**	**MS**	**F**	**Significance F**
Regression	2	284.0780809	142.0390405	10.62310461	0.02510311
Residual	4	53.48306192	13.37076548		
Total	6	337.5611429			
	Coefficients	Standard Error	t Stat	P-value	Lower 95%
Intercept	52.5558301	6.357546463	8.26668439	0.001168431	34.904451
Temperature	-0.03991739	0.010566638	-3.7776821	0.019474745	-0.06925508
Heating rate	-0.00641840	0.084339758	-0.0761017	0.094299246	-0.24058311

As it can be observed the P-value (probability level) for both parameters (heating rate and temperature) have a significant impact on the obtained biochar yield. Thus, from the Coefficients statistics we can observe that temperature parameter has a bigger influence on the biochar production yield. Similar results were obtained for straw and sorghum (Filipovici et al., 2017). The model equation was obtained creating a process matrix for predetermination of bio-char yield, using the significant regression coefficients for temperatures and heating rates.

The mathematical model obtained for the Energetic Willow is expressed by the relationship:

$$X = 52.5558 + (-0.0399) \cdot X_t + (-0.0064) \cdot X_v \quad (1)$$

where:

X – biochar yield, % mass;
X_t – final process temperature, ° C;
X_v – heating rate, ° C · min^{-1}.

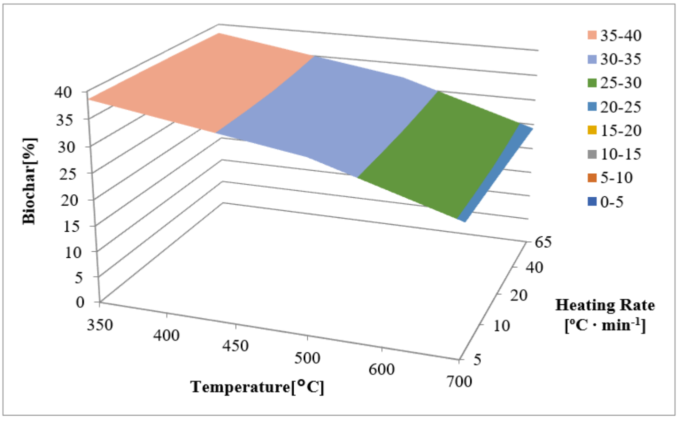

Figure 6. 3D Mathematical model representation of Salix pyrolysis char yield

Using the obtained mathematical model, it is possible to pre-set appropriate working temperature or heating rate for the pyrolysis process in order to maximize the production of biochar.

The pyrolysis process parameters used and the obtained results for biochar have close values obtained in the literature for other types of biomass: Basket willow, Parsley root peels, Potato Peels, Fiel beans, Hay had between 21.4-38.1 % of biochar (Iwanek E.M. et al., 2024). The maximum values for biochar from Energetic Willow (Salix) pyrolysis experiments were 40.88%. Results were obtained for the following set of parameters: 10 °C·min^{-1} heating rate and 400 °C temperature. Comparing the TGA-DTG experiments carried out for Energetic Willow, we can observe a similar process transformation during pyrolysis, with other biomass materials (Emiola-Sadiq et.al., 2021).

CONCLUSIONS

The content of biochar, bio-oil or syngas produced by pyrolysis of biomass is dependent on the primary and secondary reactions occurring during the pyrolysis process. From all the carried-out experiments, temperature compared to the heating rate, had a higher influence on the obtained biochar (yield) percentage. The bio-product yield from pyrolysis process can be improved by a good knowledge of the effect generated by the process parameters, leading to optimization of the system by reducing the secondary pyrolysis reactions. Furthermore, using the same mathematical model, other parameters influence such as residence time, particles size, type of inert gas, could be investigated.

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ENHANCING BIOGAS PRODUCTION FROM MISCANTHUS VIA BIOAUGMENTATION

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ABSTRACT

The increasing need for sustainable energy sources has led to a growing interest in enhancing biogas production through innovative strategies. This study investigates the effect of bioaugmentation on the anaerobic digestion of miscanthus, comparing non-bioaugmented bioreactors with miscanthus (NBBM) and bioaugmented bioreactors with miscanthus (BBM) in a 30-day continuous anaerobic digestion (AD) process. Key process parameters, including biogas and methane yield were monitored to assess the impact of bioaugmentation. The results revealed that bioaugmentation significantly increased both biogas and methane yield. Results showed that BBM achieved a biogas yield of 444.12 mL g^{-1} VS, 2.24 times higher than the 198.57 mL g^{-1} VS recorded for NBBM. Similarly, methane yield values for BBM (263.47 mL g^{-1} VS) were 2.72 times higher than those for NBBM (97.02 mL g^{-1} VS). Additionally, methane content in the biogas was enhanced from 49 % for NBBM to 54 % for BBM, demonstrating improved biogas quality. These findings highlight the potential of bioaugmentation to optimize the anaerobic digestion of miscanthus, offering a sustainable and effective approach to enhancing biogas production from lignocellulosic biomass. Future research should focus on long-term stability studies, the economic feasibility of bioaugmentation at larger scales, and exploring the impact of different bioaugmentation consortia on process efficiency.

Keywords: *bioaugmentation, anaerobic digestion, miscanthus, biogas production, enhanced methane yield*

INTRODUCTION

The global energy sector is facing growing challenges in the transition from fossil fuels to renewable energy sources. Biogas production through anaerobic digestion (AD) is a sustainable and versatile solution that is in line with international energy and environmental goals. AD converts organic material into biogas (Hans & Kumar, 2019), which consists mainly of methane (CH_4) and carbon dioxide (CO_2) (Teng et al., 2014), as well as digestate, a nutrient-rich by-product. While biogas technology is well known, ongoing research continues to focus on achieving greater efficiency and maximizing methane yield. Currently, in some countries of the European Union, maize silage is still frequently used as a primary carbon source for biogas production due to its high energy yield and reliable performance (Sobczak et al., 2022; Fuksa et al., 2020). However, the growing demand for sustainable alternatives and concerns regarding competition with food production have highlighted the need to replace maize silage with alternative energy crops. A significant incentive to shift towards non-food lignocellulosic biomass lies in its compliance with the Renewable Energy Directive (RED), which classifies biogas from lignocellulosic feedstocks as advanced biomethane. This classification offers economic advantages, as biomethane used in the transport sector is double-counted towards renewable energy targets, enhancing its market potential and policy-driven value. Among the potential feedstocks, miscanthus, a perennial C4 grass, has attracted much attention due to its high biomass yield, low input requirements and adaptability to marginal land (Naik et al., 2010; Kiesel & Lewandowski, 2014). Miscanthus can produce up to 25 t DM ha^{-1} annually, making it a promising candidate for biogas production (Whittaker et al., 2016). However, its lignocellulosic composition, which is characterized by a high lignin content (Saini i sur., 2015), poses a significant obstacle to microbial degradation during AD. Therefore, advanced strategies to improve its biodegradability are required to achieve optimal biogas yield from miscanthus.

One proposed solution, to mitigate the above mentioned challenge, is to introduce earlier harvest dates, after the first frost, when the lignin content is lower, moisture content is higher, and the aboveground biomass yield is higher comparing to the winter or spring harvests (Kiesel & Lewandowski, 2017). Huyen et al. (2010) showed that the lignin content in miscanthus harvested in November was 18.86 %, whilst it increased to 19.23 % in February. However, the increased moisture content of the biomass in earlier harvests requires appropriate storage conditions to ensure that the substrate remains suitable for continuous biogas production (Pakarinen et al., 2008). Proper storage prevents degradation and maintains the quality of the feedstock, making it suitable for optimized anaerobic digestion.

In addition to optimizing the harvest timing, bioaugmentation has emerged as a complementary strategy to further improve AD efficiency. This approach involves the introduction of specific microbial consortia to supplement and enhance the existing microbial community in the fermenter (Dadić et al. 2024). Bioaugmentation not only accelerates the degradation of complex organic materials such as lignocellulosic biomass, but also optimizes the methanogenesis phase, thus increasing biogas and methane production. Previous research has shown the potential of bioaugmentation to improve the performance of lignocellulosic substrates in the biogas production. For example, studies by Mulat et al. (2018) and Ivanković et al. (2022) showed that bioaugmentation can increase microbial activity, increase the degradation rate of the substrate and significantly increase methane yield.

Therefore, the aim of this study was to investigate the effects of bioaugmentation on the anaerobic digestion of miscanthus, comparing non-bioaugmented bioreactors with miscanthus (NBBM) and bioaugmented bioreactors with miscanthus (BBM) over a continuous AD process of 30 days. Key process parameters, such as biogas and methane production were monitored to evaluate the effectiveness of bioaugmentation. The methane content of the biogas was also analyzed to evaluate the improvement in biogas quality.

By improving the understanding of the role of bioaugmentation in the AD process, this research contributes to the broader goal of optimizing biogas production from lignocellulosic biomass. The primary focus of this study was to evaluate the effectiveness of bioaugmentation in enhancing biogas and methane yields, without delving deeply into the economic feasibility or large-scale implementation aspects. However, despite the promising potential of bioaugmentation, it is important to acknowledge challenges related to economic feasibility. The process often involves increased capital expenditures (CAPEX) for specialized microbial inoculants and higher operational costs (OPEX) due to the need for regular microbial additions and system monitoring. These factors could pose limitations for large-scale adoption, particularly in commercial biogas plants where economic efficiency is critical. The findings from this study provide a foundation for future research that will not only focus on biogas yield optimization but also consider the cost-efficiency and scalability of bioaugmentation strategies in real-world applications.

MATERIALS AND METHODS

The miscanthus samples were collected in November 2023 at the Šašinovec experimental field (45°50'59.3 "N 16°11'26.2 "E) on the University of Zagreb Faculty of Agriculture. This early fall harvest was carried out to achieve a lower lignin content. After collecting, the samples were stored at −18°C to preserve their fresh state. Prior to the anaerobic digestion (AD) process, the samples were ground to a maximum particle size of <10 mm. The fermentation substrate (inoculum) used for the AD set-up was collected from the nearest biogas plant. Before use, some of the samples were defrosted and processed into a paste, which was stored at 4°C for daily use in AD. This preparation ensured that the samples were in optimal condition for the AD process. Continuous AD was performed in a 30 L bioreactor (CROTEH d.o.o., Croatia) under mesophilic conditions at 38 ± 1.5 °C for 30 days. In the first experimental phase, miscanthus was used as the sole substrate without the addition of the bioaugmented bacteria. During the second experimental phase, bioaugmentation was applied by introducing a commercial liquid microbial consortium to enhance microbial activity. Specifically, 0.5 L of the bioaugmentation solution was added to the bioreactor on the first day of the AD process. To address stagnation of biogas production observed during the process, additional bioaugmentation doses of 0.5 L were added on the 9th and 22nd day of fermentation. This stepwise addition was intended to stimulate the microbial activity and improve substrate degradation, especially during periods of low biogas production. The biogas concentrations were measured with a portable multi-gas detector Dräger X-am 7000 (Dräger, Germany). The device was calibrated prior to use to ensure accurate measurements of methane (CH_4) and carbon dioxide (CO_2) concentrations. The total biogas produced was monitored and the data was processed to calculate the biogas and methane yield expressed in mL g^{-1} VS. The characterization of the substrate included the determination of dry matter (DM), volatile solids (VS) and chemical oxygen demand (COD). The DM was determined in accordance with HRN EN ISO 18134-2:2017. To calculate the VS, the ash content was also measured by burning the samples at 550 °C in a muffle furnace in accordance with HRN EN ISO 18122:2015. The volatile solids (VS) were calculated as the difference between the DM and ash content and COD was measured according to ISO 6060:1989. All measurements were expressed as mean values with standard deviation (STD) using TIBCO Statistica 13.3 software. The data was also processed and visualised with graphical representations which were included to improve the interpretation and understanding of the complex AD processes.

RESULTS AND DISCUSSION

The effectiveness of bioaugmentation in enhancing anaerobic digestion (AD) was evaluated by comparing the physical and chemical properties of NBBM and BBM and their biogas and methane production during a 30-day continuous process. The analysis focused on key parameters such as dry matter (DM), volatile solids (VS), chemical oxygen demand (COD), pH, biogas and methane production. The results presented below provide an insight into the effects of bioaugmentation on substrate properties, biogas quality and production efficiency.

Table 1 shows physical and chemical properties of the substrates used for the anaerobic digestion process are listed in Table 1. The dry matter (DM) content of NBBM was higher than that of BBM at 10.43 ± 0.01 %. This low DM can be attributed to the earlier fall harvest. As reported by Voća et al. (2017), the biomass harvested in spring had a higher DM content of 85.15 % due to the lower moisture content. In contrast, biomass harvested in the fall stores more moisture, resulting in lower DM values but better biodegradability of the substrate, which is beneficial for anaerobic digestion. The volatile solids (VS) content, which represent the organic fraction available for microbial degradation, remained the same for both substrates, with values of 93.34 ± 0.01 % for NBBM and 93.22 ± 0.01 % for BBM. These high VS values indicate that miscanthus remains a suitable substrate for biogas production, which is consistent with previous studies on lignocellulosic biomass (Voća et al., 2017). A notable difference was observed in the chemical oxygen demand (COD) of the substrates tested, with values of 39,157.08 ± 3,616.50 mg L^{-1} for NBBM and 49,981.67 ± 7.548.54 mg L^{-1} for BBM. These COD values are significantly lower than those of Huang et al. (2022), who determined COD values of 62.705 mg L^{-1} for miscanthus. The differences can be attributed to the different composition of the biomass, the pre-treatment methods and the harvesting conditions, all of which influence the total organic load of the substrate. The pH values for both substrates remained in the optimal range for anaerobic digestion, which supports stable methanogenic activity. For NBBM, the pH was 7.26 ± 0.13, while BBM had a slightly lower pH of 7.11 ± 0.05. Similar pH trends were reported by Špelić et al. (2024), who observed pH values between 7.0 and 7.5 for *Arundo donax* samples also in continuous AD.

Table 1. Physical and chemical analyses of the investigated samples during AD

	DM (%)	VS (%)	COD (mg L^{-1})	pH
NBBM	12.44±0.01	93.34±0.01	39157.08±3616.50	7.26±0.13
BBM	10.43±0.01	93.22±0.01	49981.67±7548.54	7.11±0.05

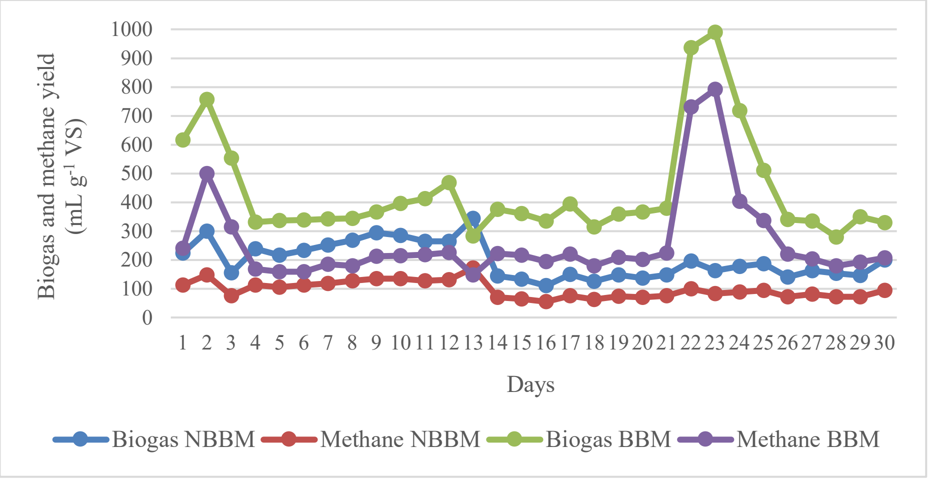

Figure 1. AD process of NBBM and BBM

Figure 1 shows the trends in the biogas and methane yield over a period of 30 days. For NBBM, the production remained relatively stable throughout the trial period. Biogas yield values ranged from about 150 to 250 mL g^{-1} VS, while methane yield values were consistently below 150 mL g^{-1} VS. In contrast, BBM consistently showed higher production levels and responded significantly to the additional bioaugmentation. Biogas yield for BBM remained at a stable baseline level of around 300–400 mL g^{-1} VS throughout most of the trial but showed a marked increase after the bioaugmentation solution was added. Peak values of above 700 mL g^{-1} VS and 800 mL g^{-1} VS were observed on day 1 and between day 21 and 25, respectively. These peaks are associated with the initial addition and subsequent reintroduction of bioaugmentation on Day 1. A similar trend was observed for methane BBM, where peak values reached approx. 500 mL g^{-1} VS on day 1 and 700 mL g^{-1} VS between days 21 and 25. The results clearly demonstrate the increased microbial activity promoted by bioaugmentation, especially during the periods of biogas production stagnation. In addition, the bioaugmented system consistently outperformed NBBM throughout the trial period, highlighting the sustained effectiveness of bioaugmentation in improving substrate degradation and biogas yield. This behaviour underlines the potential of bioaugmentation not only to maximize the methane yield, but also to provide a targeted solution to stabilize and stimulate biogas production during continuous AD process.

Table 2 shows the results for biogas composition and bigas and methane production presented as mean values for 30 days of AD. The methane content (CH_4) in the biogas produced from BBM was higher, reaching 0.54 ± 0.03 %, compared to 0.49 ± 0.02% NBBM. This increase in methane concentration highlights the positive impact of bioaugmentation on the methanogenesis phase of anaerobic digestion. In contrast, the carbon dioxide content (CO_2) was lower in BBM (0.46 ± 0.03 %) compared to NBBM (0.50 ± 0.02 %), further confirming the improved biogas quality. Specific biogas production (SBP) and specific methane production (SMP) were also notably higher for BBM. SBP values for BBM were more than double those of NBBM (444.12 ± 182.93 mL g^{-1} VS versus 198.57 ± 62.41 mL g^{-1} VS, respectively). Similarly, SMP followed the same trend, with BBM reaching 263.47 ±

154.37 mL g^{-1} VS, compared to 97.02 ± 29.51 mL g^{-1} VS for NBBM. These results are similar with Von Cossel et al. (2019) who investigated AD and methane yield of miscanthus, and who determined the average methane content in biogas of 55.1 %, with the overall methane yield of up to 270 NL kg^{-1}.

Table 2. Biogas quality and special biogas and methane production

	CO_2 (%)	**CH_4 (%)**	**SBP (mL g^{-1} VS)**	**SMP (mL g^{-1} VS)**
NBBM	0.50±0.02	0.49±0.02	198.57±62.41	97.02±29.51
BBM	0.46±0.03	0.54±0.03	444.12±182.93	263.47±154.37

CONCLUSION

This study demonstrates the significant potential of bioaugmentation in enhancing the AD of miscanthus. The results clearly show that bioaugmented bioreactors with miscanthus achieved higher biogas and methane production compared to non-bioaugmented bioreactors with miscanthus. During a 30-day continuous AD process, bioaugmentation increased the biogas yield by 2.24 times and the methane yield by 2.72 times. In addition, the bioaugmentation of miscanthus improved the biogas quality, with the methane content increasing from 49 % with non-bioaugmented bioreactors with miscanthus to 54 % for bioaugmented bioreactors with miscanthus. The improved performance of bioaugmented reactors highlights the effectiveness of bioaugmentation in overcoming the limitations imposed by the lignocellulosic structure of miscanthus. By improving substrate degradability and optimizing microbial activity, bioaugmentation offers a practical and scalable approach to increasing biogas yield from lignocellulosic biomass. These results contribute to a broader understanding of bioaugmentation as a tool to optimize AD processes and are in line with the global shift towards renewable energy solutions. Future studies should focus on validating process stability, scaling up this approach to industrial applications, and evaluating its economic viability under different operating conditions.

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50. ACTUAL TASKS ON AGRICULTURAL ENGINEERING

Original scientific paper

SUSTAINABLE USE OF AGRICULTURAL WASTE FOR HEAT BRIQUETTES: A KNOWLEDGE TRANSFER

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ABSTRACT

Agricultural waste is abundant in rural areas, where efficient heating remains a challenge, especially in older homes and underdeveloped regions. This study proposes using agricultural waste, such as crop residues and tree trimmings, as raw material for producing heating briquettes. We explore the transfer of optimized biofuel production techniques to local micro-enterprises, enabling them to manufacture heating briquettes and pellets tailored to customer demands. This approach aims to promote sustainable energy solutions while fostering local economic development.

Keywords: *biofuels, knowledge transfer, agricultural waste, sustainability*

INTRODUCTION

Sustainable development in rural communities is essential for addressing environmental challenges and fostering economic resilience. The integration of renewable resources and efficient technologies can help reduce carbon emissions, enhance energy independence, and create new economic opportunities. This, in turn, supports long-term viability and improves the quality of life for future generations.

Recent developments in rural Europe emphasize improving sustainability and efficiency. Key areas of progress include renewable energy adoption, such as solar and biomass technologies (Tucu et al., 2023), precision agriculture techniques (Babanatsas et al., 2018), circular economy practices for waste management, smart farming technologies (Ghergan et al., 2019), and the development of biofuel production systems tailored to rural contexts (Suta et al., 2021).

Agricultural activities generate significant quantities of waste, which, if left unmanaged, can lead to environmental degradation. Proper recycling and processing of residues such as crop waste and tree trimmings offer an opportunity to convert these materials into valuable energy sources. Heating briquettes and pellets produced from such residues not only improve waste management but also provide efficient, renewable heating solutions for rural households (Obernberger & Thek, 2010).

Effective agricultural waste management has a direct impact on environmental health and the socioeconomic well-being of rural regions (Marcuta et al., 2021). Improper disposal of residues contributes to air and soil pollution, harming ecosystems and public health. Transforming waste into biofuel products supports rural economies by creating jobs and stimulating local businesses. It also aligns with global sustainability goals by reducing dependence on fossil fuels and cutting greenhouse gas emissions (Gabor et al., 2023).

Recycling agricultural waste for energy production enables a circular economy approach, where residues are repurposed rather than discarded. Techniques such as pelleting and briquetting have shown promise in converting biomass into high-energy fuels, offering a sustainable alternative to traditional heating methods. Collaborating with local micro-enterprises to develop optimized production methods maximizes calorific output while ensuring emissions remain within acceptable limits. This not only minimizes environmental impact but also enhances energy security and affordability for rural communities (Waqas et al., 2023).

This study aims to present a comprehensive solution for utilizing agricultural waste by converting it into heating briquettes. It focuses on developing optimized biofuel recipes and transferring this knowledge to small-scale enterprises. By emphasizing sustainability and local economic development, the proposed model leverages agricultural residues to create efficient, customized heating solutions. While the research primarily addresses the needs of rural areas in western Romania, its applicability extends to the broader DKMT Euroregion (Euroregiunea DKMT), which spans Romania, Hungary, and Serbia. The region's abundant agricultural and forestry waste presents a significant opportunity for scalable biofuel production, offering a sustainable energy alternative that can drive economic growth and environmental resilience across diverse rural communities.

MATERIALS AND METHODS

The research presented in this study focuses on the development and application of a software tool designed to optimize the composition of heating briquettes made from agricultural waste and other biomass materials (Maris et al., 2019). The software, developed as part of doctoral research (Maris, 2022) and validated in rural biofuel production settings, enables the creation of customized biofuel recipes to maximize both efficiency and sustainability.

The briquette production process begins with the collection of agricultural and forestry waste, followed by cleaning and drying to prepare raw materials. Next, an optimization process using specialized software determines the ideal biomass mixture to maximize energy output and minimize emissions. The materials are then mixed according to the optimized recipe and compacted into briquettes. These briquettes may undergo quality checks to ensure they meet the calorific value and emission standards computed during the optimization process, before being finalized and distributed as a sustainable heating solution (Figure 1).

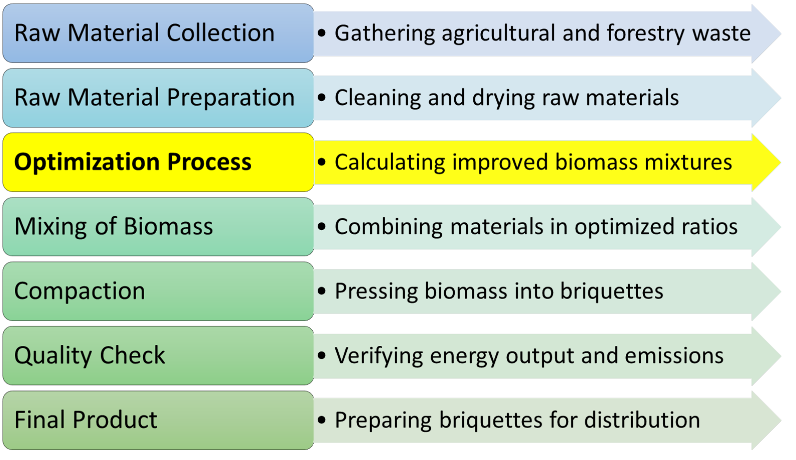

Figure 1. Flowchart of the optimized process

The following sections describe the software solution and the methods used to evaluate and optimize the quality of briquettes.

Software solution

The software was designed to assist small-scale biofuel producers, especially in rural areas with abundant agricultural waste. Its main function is to determine the optimal biomass mixture for high-energy briquettes while minimizing emissions. Using a comprehensive database of biomass properties, it calculates properties of biomass mixtures and efficient compositions for chosen components.

Developed and comprehensively tested, the software employs artificial intelligence principles (Slavici, 2016), including linear programming and optimization algorithms (Ionica et al., 2019), to simulate biofuel recipes. It adapts to new biomass materials, ensuring flexibility across different regions. Data on moisture content, ash percentage, and calorific value inform the optimization process, enabling customized biofuel recipes.

Methods and optimization techniques

The software optimizes briquette compositions using two key techniques:

- Linear programming: Solves the multi-objective problem of maximizing energy output while minimizing environmental impact. It evaluates biomass combinations based on chemical properties, moisture, and ash content to meet calorific and emission standards.
- Artificial neural networks: Refines optimization by learning from historical and experimental data. It predicts mixture properties and continuously updates its model as new data is integrated, improving accuracy.

Field implementation and testing

The software was initially validated through small-scale experiments to confirm its effectiveness in generating optimized briquette recipes. It was then implemented in a rural biofuel production facility in Cenei, Romania, to assess its industrial applicability.

This facility processes various biomass types from local agricultural and forestry activities, providing an ideal setting for real-world testing. Operators input raw material properties into the software, which calculates optimal mixing ratios. The resulting briquettes were evaluated for calorific value, ash content, and emissions (e.g., sulfur and nitrogen oxides), consistently meeting EU standards for non-woody biomass briquettes (EN 17225-1:2021, EN 17225-6:2021).

Further adjustments, such as optimizing moisture levels and adding binding agents, improved briquette durability and burn rate. The successful implementation confirmed the software's ability to enhance biofuel production efficiency and support sustainable energy practices in rural communities.

RESULTS AND DISCUSSION

Implementation and testing in a rural biofuel factory

Following its validation in a laboratory setting, the software was implemented in a rural biofuel production facility located in Cenei, Romania. This factory, which processes diverse biomass materials from local agricultural and forestry activities, served as a practical site for real-world testing.

Although the software solution can determine optimal mixtures for all pellet and briquettes standards in use, in this study, we chose to use the Mixed Biomass Pellets B (MBP B) standard. This standard was selected due to its stringent requirements for non-woody biomass briquettes, ensuring a balance between high calorific value and low emissions (Table 1). Meeting these requirements guarantees both energy efficiency and environmental compliance, aligning with European regulations on renewable energy.

Table 1. Main characteristics of the Mixed Biomass Pellets B standard

Characteristic	Unit	Value
Lower heating value (net heating value) minimum	MJ kg^{-1}	14.500
Maximum additives	% mass (dry basis)	5.000
Maximum nitrogen (N)	% mass (dry basis)	2.000
Maximum sulphur (S)	% mass (dry basis)	0.300
Maximum chlorine (Cl)	% mass (dry basis)	0.300
Maximum residual ash	% mass (dry basis)	10.000

Typical wastes in western Romania suitable for use in briquette recipes can be categorized into:

- Agricultural wastes: wheat (straw, entire plant, bran), corn (cobs, stalks, grains), sunflower (husks, stalks), barley (straw), oats (bran), rye (straw, entire plant), rapeseed (stems, cake), soybean (husks), triticale (straw, entire plant)

- Forestry and orchard waste: beech (with bark), fir and spruce (bark, chips), poplar, willow, apple and cherry (branches, leaves), vineyard waste (prunings, chips)
- Likely industrial and processing residues: sawdust and wood chips, construction wood waste

These materials are plentiful in the region and can be effectively converted into briquettes or pellets using recipes generated by the optimization software. Additionally, the raw material cost is virtually zero, as it is considered waste. This presents an excellent opportunity to implement sustainable energy solutions in rural communities.

Performance evaluation of optimized briquettes

The briquettes produced using the software-guided recipes were assessed based on key performance indicators, including calorific value and ash content. Table 2 presents the calorific values and ash content of various raw materials that are available in the geographical region (western Romania and DKMT Euroregion).

Table 2. Properties of the most common types of raw material in the area

Raw material	Calorific value [MJ kg^{-1}]	Ash content [%]
Agricultural waste		
Wheat straw	17.20	5.70
Corn cobs	17.69	2.40
Sunflower husk	17.99	1.90
Barley	17.50	4.80
Rapeseed straw	17.10	6.20
Forestry waste or processing residues		
Beech	18.40	0.50
Spruce sawdust	18.21	0.60
Construction wood	18.28	0.80
Willow	18.40	2.00

Table 3 highlights the best-performing biomass mixtures, which consistently met MBP B standards. The results demonstrate that mixtures such as sunflower husk and spruce sawdust achieved high calorific values (18.01 MJ kg^{-1}) with minimal ash content (1.81%). These optimized mixtures provide a significant improvement over traditional methods, which often rely on fixed recipes without considering material-specific properties.

Table 4 illustrates the calorific value and ash content of 2:1 mixtures of non-woody and woody biomass common to the DKMT Euroregion.

Table 3. Properties and mass ratios for highest yielding mixtures that comply with MBP B standard

Mixture	**Mass ratio** [kg:kg]	**Calorific value** [MJ kg^{-1}]	**Ash content** [% mass dry basis]
Wheat straw and spruce sawdust	77.78 : 22.22	17.38	4.79
Corn cobs and spruce sawdust	89.53 : 10.47	17.72	2.32
Sunflower husk and spruce sawdust	92.77 : 7.23	18.01	1.81

Table 4. Properties of 2:1 mixtures of non-woody biomass and woody biomass

2:1 Mixtures of non-woody biomass and woody biomass	**Calorific value** [MJ kg^{-1}]	**Ash content** [%]
Wheat straw and Beech	**17.60**	**3.96**
Wheat straw and Spruce sawdust	17.47	4.33
Wheat straw and Construction wood	17.56	4.06
Wheat straw and Willow	17.60	4.46
Corn cobs and Beech	**17.92**	**1.76**
Corn cobs and Spruce sawdust	17.79	2.13
Corn cobs and Construction wood	17.88	1.86
Corn cobs and Willow	17.92	2.26
Sunflower husk and Beech	**18.12**	**1.43**
Sunflower husk and Spruce sawdust	17.99	1.80
Sunflower husk and Construction wood	18.08	1.53
Sunflower husk and Willow	18.12	1.93
Barley and Beech	**17.80**	**3.36**
Barley and Spruce sawdust	17.67	3.73
Barley and Construction wood	17.76	3.46
Barley and Willow	17.80	3.86
Rapeseed and Beech	**17.53**	**4.30**
Rapeseed and Spruce sawdust	17.40	4.66
Rapeseed and Construction wood	17.49	4.40
Rapeseed and Willow	17.53	4.80

The DKMT Euroregion, encompassing parts of Romania, Hungary, and Serbia, offers a substantial supply of agricultural and forestry waste. In this geographical area, non-woody agricultural waste presents a significant opportunity for biomass processing. This type of waste is particularly abundant in the region's agricultural zones, which span across Romania, Hungary, and Serbia.

Romanian counties Timiș and Arad generate large volumes of non-woody agricultural residues, such as wheat straw, corn stalks, and sunflower husks, due to extensive farming practices in the fertile plains. While the counties Caraș-Severin and Hunedoara are more forested, they also contribute non-woody biomass from smaller-scale agricultural activities. Hungarian counties Bács-Kiskun, Békés, and Csongrád-Csanád, located in the Great Hungarian Plain, are heavily focused on crop production, leading to a significant supply of agricultural waste such as maize stalks, wheat straw, and sunflower husks. Serbian province of Vojvodina, a key agricultural region, produces diverse non-woody biomass, including residues from cereals, oilseeds, and sugar beets, making it a vital contributor to the Euroregion's biomass potential.

The DKMT Euroregion thus offers an extensive supply of non-woody agricultural waste that can be efficiently processed into biofuels like briquettes and pellets, supporting sustainable energy initiatives and reducing environmental impact.

These results suggest a broader applicability of the proposed method, demonstrating its potential to optimize biofuel production across diverse geographical areas within the DKMT Euroregion. This adaptability allows small-scale producers to utilize locally available resources efficiently, contributing to sustainable rural development.

Comparative advantages of the proposed method

Compared to traditional briquette production methods, the proposed optimization approach offers several advantages.

Conventional methods often involve trial-and-error processes, leading to inconsistent product quality and suboptimal energy output. In contrast, the use of advanced software ensures precise recipe development, maximizing calorific value while minimizing emissions and ash content. This not only enhances the performance of briquettes but also reduces production costs by minimizing waste and improving resource utilization.

Furthermore, the dynamic nature of the optimization software allows for real-time adjustments based on the availability of raw materials, ensuring continuous compliance with industry standards. This flexibility is particularly beneficial in the DKMT Euroregion, where biomass availability can vary seasonally.

By leveraging local resources effectively, the proposed method supports economic growth and environmental sustainability, aligning with the region’s renewable energy goals.

Implications for rural development and sustainability

The successful implementation of this method demonstrates its potential to drive rural development by creating new business opportunities and supporting local economies. By transforming agricultural and forestry waste into valuable biofuels, rural communities can reduce their dependence on fossil fuels, lower greenhouse gas emissions, and contribute to a circular economy. Moreover, the method aligns with broader sustainability objectives, promoting energy security and environmental protection across the DKMT Euroregion.

On the other side, the use of agricultural waste as biofuel presents several risks and limitations. One major challenge is the variability in biomass quality, as factors such as moisture content, ash composition, and calorific value can differ significantly between crop residues, affecting combustion efficiency and emissions. Logistical challenges also arise in collecting, transporting, and storing biomass, particularly in rural areas where infrastructure may be inadequate. Additionally, environmental concerns must be considered, such as soil depletion if excessive crop residues are removed and air pollution from improper combustion.

Effective risk management strategies include implementing standardized preprocessing techniques (e.g., drying and size reduction) to improve biomass consistency, optimizing supply chain logistics to reduce transportation costs and energy use, and adhering to strict emission regulations to minimize environmental impact. By integrating these measures, biofuel production from agricultural waste can become more reliable, sustainable, and economically viable.

CONCLUSIONS

Our study focused on the development and deployment of a software tool designed to optimize briquette mixtures for maximum energy efficiency and minimal emissions. The software calculated optimal mass ratios of various agricultural and woody biomass components, ensuring compliance with the MBP B standard. The methodology was tested and refined in a pilot factory setting, where operators utilized the software to create briquettes with high calorific values and low ash content.

The optimized mixtures consistently met or exceeded industry standards. The inclusion of woody biomass, particularly beech and willow, significantly enhanced the calorific value of the briquettes while maintaining low levels of ash and emissions. Our findings demonstrate that agricultural residues, when properly mixed and processed, can serve as a reliable and sustainable energy source. Additionally, the software's adaptability to local biomass availability ensures that rural biofuel production remains cost-effective and sustainable.

The approach presented in this paper has significant potential for scaling and application across rural areas in Europe and beyond. The combination of non-woody and woody biomass resources, optimized through software, can reduce dependence on fossil fuels and promote sustainable energy solutions. Moreover, the transfer of this knowledge to small-scale biofuel producers offers economic opportunities, supports rural development, and aligns with global sustainability goals by minimizing environmental impact.

Our current research efforts in this domain focus on multiple key aspects aimed at improving the efficiency and sustainability of biomass-based heating material production. One major area of investigation involves the automation of the production process, which seeks to enhance operational efficiency, reduce manual intervention, and ensure consistent briquette quality. Additionally, we are exploring the use of biomass additives, evaluating their potential to improve combustion properties, increase calorific value, and minimize emissions.

Future research should explore the integration of the heating material obtained from agricultural waste with other renewable energy sources (e.g. photovoltaic systems), which could optimize energy production based on seasonal variations in biomass availability. Additionally, studies should focus on the lifecycle and environmental impact of biomass, supply chain optimization (both for biomass collection and product distribution), combustion performance, and emission control. Other studies could explore the expansion of the biomass database to cover other geographical regions and industrial scaling of the software.

The solution proposed in this work demonstrates the viability of using agricultural waste for sustainable energy production. By transferring this knowledge to rural biofuel producers, we pave the way for broader adoption of renewable energy practices, contributing to a more sustainable and energy-secure future.

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USE OF COCKROACHES IN THE PROCESSING OF FOOD WASTE

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ABSTRACT

Due to their resilience and broad food spectrum, cockroaches are a potential tool for processing certain types of biodegradable waste. Through their metabolism, they convert organic material into a humus-like substrate, namely Blatticompost, which is suitable as a fertiliser for agricultural production. The aim of this paper was to demonstrate that the cockroach species Blaptica dubia and Blatta lateralis, fed with food waste, produce nutrient-rich faeces - compost - that can be used as fertiliser, and to compare the chemical and microbiological properties of the product with relevant literature sources and other ways of processing food waste. The results suggest that cockroaches have significant potential for processing food waste and producing compost. Their ability to decompose organic material leads to a reduction in the volume of waste, while the resulting compost has favourable microbiological and chemical properties. The results suggest that the use of cockroaches to process food waste could be a sustainable and environmentally friendly alternative to conventional waste disposal methods, with the added benefit of producing a high quality compost. However, the use of cockroaches in waste management requires careful management of cockroach populations to prevent the spread of these organisms outside of controlled environments. You also need to be aware of the potential risks to human health and the environment and take appropriate safety measures.

Keywords: *food waste, cockroaches, blatticomposting, processing*

INTRODUCTION

The modern world is faced with increasingly complex waste management challenges, particularly with regard to food waste and other agricultural or organic by-products. Such organic residues pose a significant environmental risk due to their composition and the potential spread of pathogens. The management of these materials involves the collection, transport, treatment and processing in an environmentally sound manner that complies with both national regulations and European directives (Salemdeeb et al., 2017). Although developed countries use advanced systems such as composting, anaerobic digestion or thermal treatments to mitigate the negative impact of food waste, the growing demand for food production and consummation continues to drive up the amount of waste requiring disposal (Xu et al., 2018).

Recent studies on different composting methods using macroinvertebrates - earthworms for vermicompost, black soldier flies for BSF compost - show that each technique leads to different physicochemical and microbiological profiles that affect the quality of the final product. Vermicompost (produced by earthworms such *as Eisenia fetida* or *Eudrilus eugeniae*), for example, typically has a total nitrogen (N) content of 1.5–3.0%, a phosphorus (P_2O_5) content of 1.0–2.0% and a potassium (K_2O) content of 1.0-2.5, with a pH of 6.0–7.0 and a moisture content of 60% to 80% (Edwards et al., 2010; Lim et al., 2015). Thanks to its high microbial load and improved biological activity, vermicompost is highly valued in organic farming and horticulture. In addition, BSF compost produced by black soldier fly (*Hermetia illucens*) larvae also shows promising data: about 1–2% N, 0.6–1.2% P and 0.8–2% K, paired with a pH of 6.5–7.5 and a moisture content of 50–70% (Insam et al., 2010; Smetana et al., 2019). The larvae of the black soldier fly efficiently degrade large amounts of organic waste within two to three weeks and reduce the total mass by up to 50%. A new approach suggests using cockroaches for the bioconversion of waste materials. Initial studies suggest that cockroaches can break down a wide range of organic waste, including meat and protein-rich residues. By metabolising these materials, cockroaches can significantly reduce the overall volume of waste and produce nutrient-rich by-products that can be used as compost (Adedara et al., 2022; Poma et al., 2017). However, to fully assess feasibility, population control measures, biosafety guidelines and potential risks to human health and the environment must be considered (Wang and Shelomi, 2017).

In recent years, blatticomposting has gained attention - using certain cockroach species such as *Blaptica dubia*, *Blatta lateralis*, *Aeluropoda insignis* or *Eublaberus s*p. In contrast to conventional “garden compost",” which usually contains about 0.5–2% N, 0.3–1% P and 0.5–1.5% K (Haug, 1993), some studies indicate that the content of certain macronutrients in blatticompost is occasionally higher, depending on the cockroach species and source material. Patón and García-Gómez (2023) report nitrogen contents in certain cockroach-derived composts of 3.13% to 3.575%, at a pH of about 6.78 to 7.29. In other experiments, somewhat more modest values were obtained (e.g. ~1.4–1.7% N, 0.3–0.4% P_2O_5, 2.0–2.5% K_2O), which are comparable to standard garden compost or the lower end of BSF compost (Adedara et al, 2022). The moisture content of blatticompost is usually between 40–70%, the pH is often neutral or slightly alkaline (7.0–7.9) and the electrical conductivity usually remains below 4 mS/cm.

These variations are largely due to the different trophic preferences of the cockroaches and the differences in feeding material. When the insects consume substrates with a higher mineral content — such as slaughterhouse waste or cooked leftovers — the resulting compost may have a higher electrical conductivity or a higher ash content (Patón and García-Gómez, 2023). Conversely, feed consisting of fruit and vegetable waste often has a higher moisture and organic matter content, but slightly lower phosphorus and micronutrient concentrations (Adedara et al., 2022).

Overall, vermicompost, BSF compost and blatticompost offer the potential to effectively reuse organic waste and produce a nutrient-rich substrate. Vermicompost and BSF compost are already widely used, while blatticomposting is only gradually gaining in importance. A key advantage of cockroach-based methods is their ability to process different types of waste — especially fat- or protein-rich materials, which is more flexible than some other methods. The main challenge is to ensure closed and controlled facilities to prevent the cockroaches from spreading outside the intended environment (Wang and Shelomi, 2017).

In this context, the present research aims to investigate a new method of composting food waste with cockroaches (species *Blaptica dubia* and *Blatta lateralis*) and to compare the chemical and microbiological properties of the resulting substrate - "blatticompost" - with the existing literature on composting by other biological means. By describing both the experimental set - how the cockroaches were reared and fed — and the subsequent results, which reflect the nutrient content of the compost and the absence of pathogens, the study emphasises the potential of cockroach-based methods for sustainable waste management.

MATERIALS AND METHODS

Due to their availability from specialised suppliers, the cockroach species *Blaptica dubia* and *Blatta lateralis* were selected for this study on the decomposition of food waste. These species differ in biological characteristics such as social behaviour, trophic preferences, reproduction, growth rate, body size, etc.

In nature, *B. dubia* inhabits the leaf litter in the tropical forests of northern South America. These conditions — high humidity, high temperatures and predation pressure — have driven the species to rapid reproduction and larger nymphs at hatching. *B. dubia* tolerates a high population density, typically at a ratio of five females per male. The exoskeleton of this species is relatively soft and contains less chitin, resulting in higher protein content, but requires controlled humidity, especially for the nymphs that dehydrate easily. Adults are usually about 4.0–4.5 cm in size. Males have full wings, while females have only small wing stubs (Figure 1). They are ovoviviparous and give birth to 20–40 nymphs per month under optimal conditions (Hao, 2013). The ideal temperature range for reproduction is 24–35 °C; egg carton stacks and good ventilation help to keep the environment dry and reduce bacterial or fungal growth (Appel, 2004).

Figure 1. *B. dubia* male (left) and female (right) used in investigation

B. lateralis is native to the arid regions of the Arabian Peninsula and is well suited to captivity. This species usually grows to about 3 cm in length and exhibits strong sexual dimorphism (Bell et al., 2007). Males are slender and have yellowish wings, while females are slightly darker and broader and have only rudimentary wings (Figures 2). Due to its ecological adaptation to Mediterranean climates, *B. lateralis* can be kept in captivity without substrate, similar to *B. dubia*. Its main advantage is its high reproductive capacity (Shal, 1983). Although this species is generally not considered a pest, it can be found in tropical regions near human dwellings, especially adult males that can fly and are attracted to light (Appel, 2004).

Figure 2. *B. lateralis* male (left) and female (right) used in investigation

In this study, eight plastic containers (four for each cockroach species), each with a capacity of 22.44 dm³, were used and equipped with a thermometer and a hygrometer to monitor temperature and humidity on a weekly basis. Both species were kept at 25 °C (±2 °C) and approximately 70% (±5%) relative humidity. Each container housed 100 cockroaches in a ratio of five females to one male, plus nymphs - together with cardboard material (e.g. egg cartons) for movement, moulting and light protection (Figure 3). A securely sealed system with 1 mm ventilation holes prevented the escape or entry of external pests (such as *Drosophila melanogaster* or *Musca domestica*).

Over a period of two months, they were fed once a week under controlled temperature, humidity and light conditions with approximately 20 grammes of food waste corresponding to their physiological needs. These food wastes consisted of various foods that are also used in cockroach rearing, such as bananas, apples, carrots or pelleted cat food. Over the course of 10 weeks, the faeces were collected to compare the efficiency of waste decomposition.

The final product, the blatticompost, was subjected to chemical and microbiological analyses. The excretion samples from each container were collected weekly in sterile 100 ml plastic cups. Each sample was analysed in triplicate. Analyses included moisture content, total solids, pH, electrical conductivity, organic carbon, organic matter, total nitrogen, phosphorus, potassium, calcium, magnesium, manganese, iron and heavy metal concentrations.

The samples (10 g each) were dried at 105 °C, then ground and homogenised, following the protocols of the Plant Nutrition Laboratory of the Faculty of Agriculture. The moisture and dry matter content was measured gravimetrically at 105 °C (HRN EN 12048:2001). Ash was determined by incineration (HRN EN 13039:2012). The pH value (in 10% aqueous solution) was determined according to HRN ISO 10390:2004, and the electrical conductivity (also in 10% solution) was measured by conductimetry. Organic carbon was calculated using the dichromate method, organic matter from organic carbon. Total nitrogen was determined using the Kjeldahl method (HRN EN 16169:2013). Using HRN EN ISO 54321:2021, total phosphorus (P_2O_5), potassium (K_2O), calcium (Ca), magnesium (Mg), manganese (Mn) and iron (Fe) were extracted with aqua regia and measured spectrophotometrically or by atomic absorption spectrometry. The heavy metal concentrations were measured using AAS, whereby the maximum permissible values in accordance with the Directive on the Protection of Agricultural Land against Pollution of Croatia (OG 71/2019) were observed.

In the microbiological tests, Salmonella spp., Shigella spp., E. coli and Campylobacter spp. were examined according to the standardised approach of HRN EN 12880:2005. The 10 g of each sample was weighed and processed at the Institute of Public Health “Dr Andrija Štampar”. The presence of Salmonella spp., Shigella spp., E. coli and Campylobacter spp. was determined by selective enrichment (e.g. PPV with Novobiocin) and subsequent plating on SS agar, PP agar, KARMALI agar and PING agar. Each agar was incubated at specific temperatures and for a specific duration to accurately isolate and identify potential pathogens.

RESULTS AND DISCUSSION

The analysis of blatticompost produced by two food waste-fed cockroach species (*B. Dubia* and *B. Lateralis*) is shown in Table 1.

Water content and dry matter are important indicators for understanding the chemical and biological processes involved in composting. By analysing the values obtained and comparing them with literature data, it is possible to determine how these parameters influence compost quality. The recommended moisture range for compost is between 40 and 60% (Haug, 1993). According to the data presented in Table 1, the *B. dubia* compost had a moisture content of 73.52% and only *B. latteralis* was in the optimum range at 50.36, indicating a moisture content suitable for microbial activity. A balance between dry matter and moisture is crucial for maintaining aeration and optimising microbial processes. The recommended range for dry matter is also 40–60% (Azis et al., 2023). As can be seen in Table 1, *B. lateralis* is within this range (49.64%), while *B. Dubia* (26.48%) has lower values for dry matter. The lower dry matter could be due to a higher proportion of wet feed (fruit peel, vegetable scraps). Such wet feeding must be carefully adjusted to ensure a sufficient nitrogen content (Haug, 1993). In addition, high moisture content can create anaerobic conditions that favour acid production and a drop in pH while inhibiting oxidative processes (Sundberg et al., 2004).

The pH value of the soil is a measure of the acid or alkali content, which is determined by the hydrogen ion concentration. The pH value of the soil has a direct influence on the availability of nutrients in plants. For example, under acidic conditions (below pH 5.5), certain micronutrients such as iron or aluminium can be more soluble and potentially toxic (Oshunsanya, 2019). In alkaline soils (above pH 7.5), the availability of phosphorus, iron, manganese and zinc usually decreases (Marschner, 2012). Microbial activity also depends on pH. Acidic soils can inhibit certain decomposers, while alkaline conditions can reduce nitrogen-fixing bacteria (Brady and Weil, 2016). In this study, the pH ranged from 5.07 for *B. Dubia* to 7.87 for *B. lateralis*. According to Othman et al. (2012), vermicompost has a pH of 6.8, while garden compost often has a pH of 7.8. Here, the cockroach-derived samples ranged from slightly acidic to slightly alkaline, which corresponds to typical guidelines for plant growth. The lowest pH value could result, for example, from feeding with citrus peel and higher moisture (Hillel, 2004).

Table 1. Analysis of blatticompost produced from food waste

Blatticompost analysis	B. Dubia	B. Lateralis
Moisture (%)	73.52	50.36
Dry matter (%)	26.48	49.64
pH	5.07	7.87
EC (mS/cm)	2.07	3.52
Žareni ostatak (Ash) (%)	13.97	22.41
Organic matter (%)	86.03	77.59
TOC (%)	48.18	43.45
Nitrogen (% in d.m.)	1.44	1.71
Phosphorus (% in d.m.)	0.29	0.37
Potassium (% in d.m.)	2.01	2.56
Calcium (% in d.m.)	0.77	0.78
Magnesium (% in d.m.)	0.15	0.20
Manganese (g/kg in d.m.)	1.22	1.50
Iron (mg/kg in d.m.)	56.70	36.40
Zinc (mg/kg in d.m.)	112	39,5
Copper (mg/kg in d.m.)	20.6	14.7
Cadmium (mg/kg in d.m.)	<0,1	<0,1
Lead (mg/kg in d.m.)	2,75	3,01
Nickel (mg/kg in d.m.)	12,8	21,4
Chromium (mg/kg in d.m.)	21	31,8
Mercury (mg/kg in d.m.)	<0,1	<0,1
Arsenic (mg/kg in d.m.)	<0,1	<0,1
Molybdenum (mg/kg in d.m.)	0,35	0,18
Cobalt (mg/kg in d.m.)	0,7	0,98

Electrical conductivity (EC) evaluates the ion concentration in a sample. The optimum EC value for most plants is between 0.2 and 1.2 mS/cm and ensures sufficient nutrient supply without excessive salinity (Weil and Brady, 2017). The recommended EC value for compost is between 1.0 and 4.0 mS/cm (Dominguez et al., 2011). Here, the EC value of blatticompost was measured at 2.07 for *B. dubia* and 3.52 mS/cm for *B. lateralis* and was thus well within the permissible limits. Othman et al. (2012) observed a significantly higher EC value in vermicompost (11.70 mS/cm) than in these samples. Patón and García-Gómez (2023) reported average EC values in blatticompost of 5.36 mS/cm, which is slightly above the European guideline value of 4 mS/cm, possibly due to the high salt content in cooked food waste. A high EC value may indicate an oversupply of salts/nutrients, leading to salt stress in plants (Munns and Tester, 2008; Shannon and Grieve, 1999).

The ash content refers to the mineral residue that remains after the combustion of organic material. In the literature, it is assumed that the ash content is between 20–50%, depending on the source material and process (Haug, 1993). Table 1 shows values of 13.97% for *B. dubia* and 22.41% for *B. lateralis*. A higher ash content means that the feed is rich in minerals and has the potential for more macro- and micronutrients. However, an excessive of minerals can increase the pH and reduce the availability of nutrients. Lower ash content indicates higher organic matter, which is beneficial for soil structure and water retention (Haug, 1993).

The organic matter in dry matter (OM) indicates the total mass of organic substances. The recommended OM in compost is between 40 and 60% (Haug, 1993). The samples of *B. dubia* showed 86.03% and *B. lateralis* 77.59%. Patón and García-Gómez (2023) describe that the differences between the samples may reflect different diets, feeding routines and biological characteristics. The total organic carbon (TOC) in the dry matter measures the carbon from organic substances in the sample. The recommended TOC value is 40–60% (Weil and Brady, 2017). The samples of *B. dubia* show 48.18% and *B. lateralis* 43.45%, which means that the TOC value is lower, possibly due to high-protein, high-fat feed. Future research should investigate metabolism in specific cockroach species to clarify these results.

Nitrogen (N) is an essential macronutrient for plant growth (proteins, enzymes, chlorophyll). The total nitrogen content in dry matter was between 1.40% and 1.71%, which is well in line with the values for vermicompost (1.33% or higher), conventional compost (1.05%) and BSF compost (1.45%) reported by Jadia and Fulekar (2009), Othman et al. (2012) and Widyastuti et al. (2021). Patón and García-Gómez (2023) found higher N contents (3.13–3.57%) in blatticompost from other cockroach species, suggesting that the type of cockroach and forage influences the nitrogen content. Phosphorus (P_2O_5) is crucial for root development and flowering, optimally 0.3–0.5% in compost (Brady and Weil, 2002). Here, P_2O_5 was between 0.29-0.37%. Although these values are close to the lower threshold, they are acceptable. Other studies have shown higher P_2O_5 values in vermicompost (0.47%), garden compost (0.35%) and BSF compost (1.58%) (Othman et al., 2012; Widyastuti et al., 2021). Patón and García-Gómez (2023) also reported slightly elevated P_2O_5 values for blatticompost derived from other roach species, highlighting the potential variability due to feed composition. Potassium (K_2O), which is important for osmotic regulation and the activation of enzymes, is usually 1.5–3% in compost (Rynk et al., 1992). The values here were 2.01–2.56%, which corresponds to the recommended values. In the literature, vermicompost is given as 0.70% K_2O and garden compost as 0.48%, both of which are below these results (Othman et al., 2012). Patón and García-Gómez (2023) observed 1.47–2.06% K_2O in roach-based compost, comparable to the results here. Calcium (Ca) is vital for cell walls, root growth and buffering the acidity of the soil. A content of 0.5–2% is recommended for compost (Brady and Weil, 2002). The samples contained 0.77–0.78%, which is an appropriate level. Magnesium (Mg), which is important for chlorophyll, is optimal at 0.1–0.5% (Epstein, 2011). Our results confirm that the Mg is sufficient for plant uptake.

Manganese (Mn) is important for photosynthesis and cell division, but recommended compost levels are generally between 0.01- 1.0 g/kg (Rynk et al., 1992). Here, the Mn content was significantly higher at 1.22-1.50 g/kg. Iron (Fe), which is recommended at 50–500 mg/kg, was within an acceptable range at 36.4-56.7 mg/kg.

Zinc (Zn) is essential, but toxic in high concentrations. Local regulations (OG 71/2019) allow 150 mg/kg Zn at a pH of 5–6 or 200 mg/kg at a pH of >6. Our range (39.5–112 mg/kg) complies with the legal limits. Copper (Cu) also remains below the limit of 90–120 mg/kg (14.7–20.6 mg/kg). Cadmium (Cd), which is toxic even in small amounts, remained below 0.1 mg/kg and thus safely below the limit value of 1.5–2 mg/kg. Lead (Pb) was at 2.75–3.01 mg/kg and thus below the upper limit of 100–150 mg/kg. Nickel (Ni), which is regulated at 50–75 mg/kg, was 12.8–21.4 mg/kg. Chromium (Cr), which is below 40–80 mg/kg, was registered at 21.0–31.8 mg/kg. Mercury (Hg) was <0.01 mg/kg and thus below the standard of 1–1.5 mg/kg. Arsenic (As) <0.1 mg/kg, well below the limit of 25–30 mg/kg. Molybdenum (Mo), which is limited to 15 mg/kg, was measured at 0.18–0.35 mg/kg. Cobalt (Co), which is limited to 50–60 mg/kg, was in the range of 0.70–0.98 mg/kg. All heavy metals in these composts were therefore below the legal limits (OG 71/2019), which makes them acceptable for agricultural soils.

Microbiological safety is of critical importance, especially with regard to Salmonella spp, Shigella spp, E. coli and Campylobacter spp. If these pathogens are present, they can pose a health risk by contaminating products. Here, none of these bacteria were isolated in 10 g wet weight from any sample, apart from inconclusive results on SS agar (Fig. 40). Additional MALDI-TOF analyses confirmed the absence of the targeted pathogens, although Pseudomonas aeruginosa was found, which does not pose a risk to the environment (HRN EN 12880:2005). Table 2 shows the microbial results for both B. dubia and B. lateralis compost. The absence of these pathogens indicates that the finished compost is microbiologically safe and suitable for agricultural use without an increased risk of transmitting pathogens to crops or humans who consume them.

Table 2. Compost analysis results for *B. dubia and B. lateralis* samples

Bacteria	Results
Salmonella spp.	Not isolated
Escherichia coli	not isolated
Shigella spp.	Not isolated
Campylobacter spp.	Not isolated

CONCLUSION

The compost quality of cockroaches was measured not only by nutrients, but also by other indicators such as organic matter, pH and moisture content. Both species, Blatica dubia and Blatt lateralis, produced high quality compost, but there are subtle differences that could have an impact on certain agricultural applications. The study also showed that all samples had heavy metal concentrations below the maximum permitted levels, confirming their safety for use on agricultural land. The microbiological analyses revealed no occurrence of the pathogenic bacteria tested, further confirming the microbiological safety of the blatticompost.

The tests carried out showed significant differences in the chemical properties between two cockroach species, Blaptica dubia and Blatta lateralis. The results of the chemical analyses showed variations in the parameters indicating that the biological characteristics, the trophic habits of the cockroaches and the substrate they feed on significantly influence the quality of the produced blatticompost.

In the context of agricultural applications, the compost produced by these cockroaches has considerable potential. Depending on the material selected for feeding the cockroaches and the rearing conditions, it is possible to customise the process to produce compost with an optimal composition for specific agronomic needs. The use of such compost can contribute to more sustainable agriculture by reducing the use of chemical fertilisers and making better use of organic waste.

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50. ACTUAL TASKS ON AGRICULTURAL ENGINEERING

Original scientific paper

AN ALTERNATIVE BIOMASS RESOURCE FROM POKEWEED BERRIES USED AS BIO-COLORANT IN WOOL ECO-DYEING

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ABSTRACT

There is an increased concern related to synthetic dyes, so that natural dyes have become very popular over the last decades, particularly those extracted from renewable or sustainable resources. In the present paper, we investigated the valorization as biocolorant for wool dyeing of the red fruits of pokeweed (Phytolacca americana), a very accessible plant considered a pest species by farmers.

The dyeing process with fruit biomass pigments was performed using two technologies, the conventional procedure at 80°C and the ultrasound-assisted technique, through meta-mordanting treatment, in the presence of metal and/ or natural mordants (tannic acid, citric acid, ferrous sulfate II, copper sulfate with oxalic acid, ferrous sulfate with oxalic acid), added at two concentrations, 3% and 5% respectively.

The dyed wool samples were evaluated comparatively with untreated fabrics with regard to dye or mordants, for color properties by the CIELAB system, for resistance to both wet and dry rubbing and for structure changes through FT-IR analysis. The applied biomordants stabilized the fuchsia/ red/ orange color by 1-1.5 points during various treatments in the exploitation of dyed products based on protein fibers. In relation to different wool dyeing conditions in the presence of the pokeweed aqueous extract, the dyed fabrics acquired beautiful and long-lasting colors.

The obtained results point out the promising biomass pigments to be further researched for obtaining sustainable and safe products intended for various applications, using friendly technologies of dyeing.

Keywords: *pokeweed, wool fabrics, dyeing procedures, biomordants, CIELAB*

INTRODUCTION

The growing interest in sustainable practices, coupled with several environmental concerns from dyeing and finishing textile products has directed attention towards the use of plant-based dyes, which offer an eco-friendly alternative to synthetic textile colorants. Synthetic dyes, while cost-effective and highly stable, contribute significantly to environmental pollution and may pose health risks due to the presence of toxic chemicals (Pizzicato et al., 2023). As a result, the search for natural dye sources has become a priority, especially in the context of abundant renewable and less harmful resources. Natural dyes are biodegradable, non-toxic, and often exhibit antimicrobial properties, making them an attractive alternative for a sustainable textile production (Li et al., 2022). Among these natural sources, plants have proven to be particularly valuable due to their wide range of pigments. One such promising sustainable plant source of biocolorants for wool dyeing is represented by the red fruits of *Phytolacca americana*.

P. americana, commonly named Pokeweed, Poke Salad or Pokeberry, is an annual herbaceous plant, native to North America. Although it typically grows as an annual, it can exhibit perennial behavior under certain conditions. The plant has now become established in parts of Europe and Asia, where it has been introduced, being considered invasive. It grows to a height of 1 to 3 m, its stems can vary in color, appearing distinctly red, pink, or purple (Xu et al., 2023). The flowers, which hang in clusters, are green or white and eventually develop into deep purplish-black berries. These berries are an important food source for many bird species, including cardinals, mockingbirds, brown thrashers, and more. The parts of the plant have historically been used in traditional medicine and as food sources, but they require specific processing (Ravikiran et al., 2011). Therefore, when using and storing pokeberries for dyeing, careful attention must be employed. Most berries of different plants produce unstable dyes that quickly fade to gray, but pokeberries are an exception, offering bright colors right from the start.

The pokeberry dye is most effective on animal fibers like wool, providing luminous and unique fuchsia red and orange colors. Wool has been utilized for centuries, not only as a textile material but also for its medicinal properties. In ancient times, wool was revered for its ability to protect and heal the body, a belief supported by its use in various cultures for wound care (Martínez-García, 2023). Modern medicine has continued to explore and validate these traditional uses. Applications in the medical textile sector are favored due to their benefits, including superior insulation, biocompatibility, non-allergenic and non-toxic for the human body (Singha et al., 2022). Wool's breathability and moisture-wicking capabilities help keep wounds dry and reduce the risk of infection, making it a valuable material for bandages and dressings. Wool bandages are biodegradable and provide a sustainable alternative to traditional plastic bandages.

Bio-mordants, derived from natural sources, help fix the dye onto the fiber, resulting in better color retention and resistance to washing and light exposure. Moreover, the application of bio-mordants has been explored to enhance the dye depth and improve the fastness properties of the dyed wool (Repon et al., 2024). This approach not only improves the quality of the dyed wool fabrics, but also maintains the eco-friendly nature of the dyeing process (Salem and Al Amoudi, 2020).

Despite its reputation as a noxious weed, the fruits of *P. americana* offers readily available colorants and could be valorized as a sustainable dyestuff source, offering a dual benefit of managing a problematic species while providing a renewable source of dye.

Previous studies reported the influence of different operational parameters of wool dyeing with *P. americana*, *e.g.* time, duration, temperature and thermal degradation, while less studies dealt with the influence of mordants (Wang et al., 2012).

The aim of the present study was to investigate the influence of using mordanting with natural and classic mordants added at different concentrations in the wool dyeing with an aqueous fruit extract of *P. americana*, on color and strength properties of protein fibers, applying a conventional dyeing method and an ultrasound-assisted procedure.

MATERIALS AND METHODS

Plant material and preparation of aqueous extract from P. americana fruits

Pigments from 10 g of *P. americana* L. fruits, harvested from „Anastasie Fatu" Botanical Graden, Iasi, Romania (47°11'12.5"N; 27°33'14.3"E), were extracted using 100 mL of distilled water at 40°C. Maceration was carried out at room temperature for 24 h under occasional stirring, followed by centrifugation at 8000 rpm for 10 min at 4°C using the Universal 320 R centrifuge (Hettich, Germany).

Dyeing processes of protein fiber samples

The textile fabrics were obtained from 100% wool fibers, having a weight of 212 g/m², and a thread fineness of 20 Nm. The chemical reagents utilized in the experiment, citric acid, tannic acid, oxalic acid, copper sulfate and iron sulfate (Scharlau S.L., Spain) were of analytical grade.

The two dyeing processes, conventional – exhaust, and ultrasound-assisted dyeing, were conducted on wool fabric samples both in the presence and absence of biomordants (citric and tannic acids) and standard mordants (copper sulfate and iron sulfate). Each dyeing experiment involved the use of two mordant concentrations: 3% and 5%, respectively. Additionally, a mixture of 4% iron sulfate and oxalic acid was used relative to the textile material's weight. Each method was applied for 15 min at a 25:1 liquid ratio. The conventional dyeing method was performed at 80°C, while the ultrasound-assisted procedure was conducted at 40°C using an Elmasonic E Ultrasonic bath.

ATR-FTIR analysis of dyed samples

The changes in the chemical composition of colored wool samples were examined using the Attenuated Total Reflection-Fourier Transform Infrared (ATR-FTIR) spectroscopy. This analysis was conducted at a resolution of 4 cm^{-1} using a Bruker ATR-FTIR spectrometer (Germany), incorporating both ZnSe ATR and QuickSnap™ modules.

Color measurements of dyed wool fabrics

The chromatic analysis of the wool samples dyed with *P. americana L*. fruit extract, in the presence and absence of mordants, was conducted using a Datacolor 110 LAV reflection spectrophotometer and the Tools II Plus software. The evaluation was performed under D65/10° illumination/observer conditions to measure the chromatic parameters: L* (lightness), a* (red-green), b* (yellow-blue), C* (chroma), and h (hue). The total color change (ΔE*) was calculated by comparing these values to a reference sample.

Assessment of fastness properties of dyed wool fabrics

The dyed samples were tested for color fastness to washing and to rubbing according to standard methods (ISO-105-C10, 2007; ISO-105-X12, 2016) using the Crockmaster equipment. The color resistance of the samples was tested both before and after the meta-mordanting treatment.

RESULTS AND DISCUSSIONS

ATR-FTIR analysis of eco-dyed wool samples

Figure 1 and Figure 2 present the results of the ATR-FTIR analysis conducted to identify the major functional groups present in samples, which were dyed using the exhaustion and ultrasound-assisted methods, with *P. americana* berries extract.

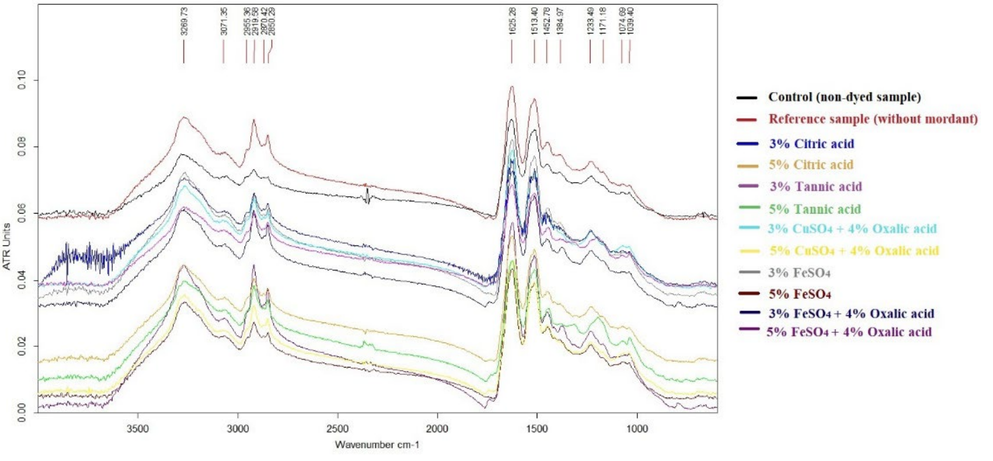

Figure 1. ATR-FTIR spectra of investigated wool samples, dyed by exhaustion (E) with *P. americana* fruit extract, in the presence and absence of mordants

The broad absorption bands at 3269.73 cm^{-1} (E) and 3271.47 cm^{-1} (US) were attributed to the alcoholic/ phenolic/ aqueous hydroxyl (−OH) bond stretching vibration. The sharp absorption bands at 3071.35 cm^{-1} (E) and 3064.34 cm^{-1} (US) are linked to sp^2 C-H stretch (aromatic C-H), while the bands at 2955.36 - 2850.29 cm^{-1} (E) and 2953.24 - 2850.50 cm^{-1} (US) correspond to sp^3 C-H stretch (aliphatic C-H). The sharp bands at 1625.28 cm^{-1} (E) and

1625.66 cm⁻¹ (US) confirm the presence of a carbonyl group (C=O) in the stretching vibration mode, associated with an amide bond (Misra et al., 2022). The absorption bands at 1513.40 cm⁻¹ (E) and 1514.18 cm⁻¹ (US) suggests the presence of a bending aromatic (C=C) bond or N-H bending (amine) (Mansour et al., 2022). The bands at 1452.78 cm⁻¹ (E) and 1448.42 cm⁻¹ (US) indicate the presence of methylene groups (CH_2) bending. Additionally, bands at 1384.97 cm⁻¹ (E) and 1386.21 cm⁻¹ (US) stands for methyl group (CH_3) bending. The peaks at 1233.49 cm⁻¹ - 1039.40 (E), and 1228.96 cm⁻¹ - 1038.69 (US), respectively, can be attributed to C-O-C functions of ethers and esters.

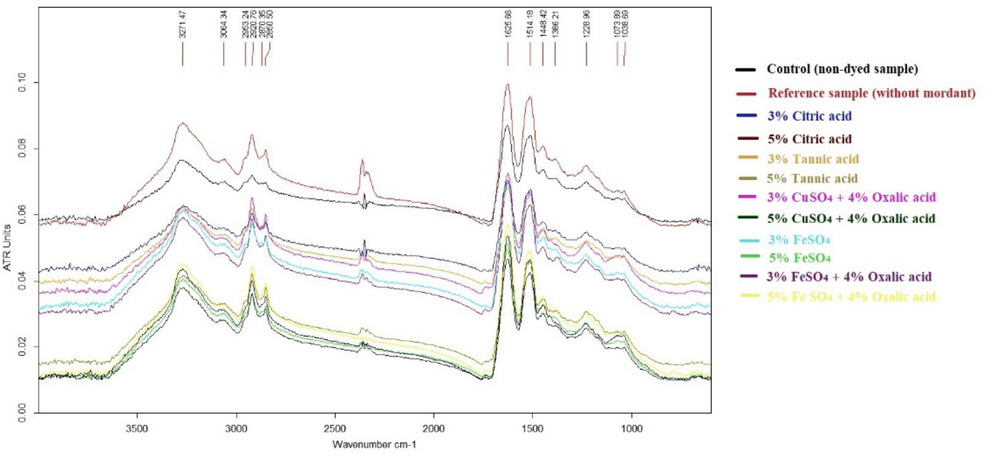

Figure 2. ATR-FTIR spectra of investigated wool samples, dyed by ultrasound-assisted method (US) with *P. americana* fruit extract, in the presence and absence of mordants

The application of mordants did not notably alter the structure of the wool fiber and did not create any differences, compared to the structure of the reference samples (dyed without the aid of mordants). The bands at 1625.28 cm⁻¹ (C=O stretching) were found more intense in the citric acid-treated samples, suggesting an effective incorporation of citric acid. The band at 1452.78 cm⁻¹ (C-H bending) was more pronounced, indicating a successful treatment with $FeSO_4$ mordant. According to (Liu et al., 2014), given that the *P. americana* dye is water-soluble and contains carboxyl groups, it interacts with the protonated amino groups of wool fibers under acidic pH environment through an ion exchange reaction. *Phytolacca* dyes adhere to wool fibers due to the formation of ionic bonds between the dye molecules and the fibers carboxylic groups. Additionally, weak secondary interactions, such as hydrogen bonding and van der Waals forces, also contribute to interactions between the dye and the fiber.

Color analysis and durability assessment of eco-dyed wool samples

The color change assessment was conducted to understand the impact of the investigated mordants and to predict the effects of different treatments applied to the dyed materials. Regardless of the destination of the products, to assess stability of the dye, the resistances to washing and rubbing are evaluated.

Table 1. Colorimetric parameters and fastness evaluation values for wool samples dyed with *P. americana L.* fruit extract using conventional and ultrasound-assisted techniques

Dyeing method / Mordant used	ΔL*	Δa*	Δb*	ΔC*	ΔH*	ΔE*	Washing fastness	Dry rubbing fastness
CONVENTIONAL PROCEDURE								
Reference sample (REH)	64.27	16.28	8.78	18.50	28.34	-	2-3	3
3% Citric acid (CA3)	-25.40	18.53	-2.64	16.85	-8.15	31.55	3-4	3
5% Citric acid (CA5)	-25.12	17.98	1.37	17.23	-5.30	30.92	4	4
3% Tannic acid (TA3)	0.40	-4.92	3.42	-1.83	5.71	6.01	4-5	4
5% Tannic acid (TA5)	0.00	-5.90	2.80	-2.95	5.83	6.53	5	4-5
3% $FeSO_4$ (iron sulfate) (IS3)	-4.60	13.58	8.40	-1.10	15.93	16.62	3-4	3
5% $FeSO_4$ (iron sulfate) (IS5)	-2.60	-13.97	7.80	-1.76	15.90	16.21	3-4	3-4
3% $CuSO_4$ + 4% Oxalic acid (CS3)	-4.81	-4.32	18.22	11.04	15.13	19.34	3-4	4
5% $CuSO_4$ + 4% Oxalic acid (CS5)	-3.32	-3.15	19.93	13.08	15.37	20.45	4	4
3% $FeSO_4$ + 4% Oxalic acid (IO3)	-6.72	-1.87	12.10	6.87	10.13	13.96	3-4	3
5% $FeSO_4$ + 4% Oxalic acid (IO5)	-2.44	-4.10	17.43	10.41	14.57	18.08	4-5	4-5
ULTRASOUND-ASSISTED PROCEDURE								
Reference sample (RUS)	65.90	15.91	4.93	16.65	17.21	-	2-3	2-3
3% Citric acid (CA3)	-21.71	16.85	-6.73	16.15	-8.26	28.29	4	3
5% Citric acid (CA5)	-23.81	18.12	-4.95	17.37	-7.14	30.32	4	4
3% Tannic acid (TA3)	4.13	- 6.46	1.28	-5.34	3.85	7.77	4-5	4
5% Tannic acid (TA5)	4.09	-6.76	1.11	-5.69	3.82	7.98	4-5	4-5
3% $FeSO_4$ (iron sulfate) (IS3)	-3.84	-11.68	8.55	-2.53	14.25	14.98	4-5	3-4
5% $FeSO_4$ (iron sulfate) (IS5)	-4.65	-12.17	8.38	-2.83	14.50	15.49	5	4-5
3% $CuSO_4$ + 4% Oxalic acid (CS3)	-4.12	-4.26	8.29	0.97	9.27	10.19	4-5	4
5% $CuSO_4$ + 4% Oxalic acid (CS5)	-2.75	2.67	7.01	1.17	7.41	7.99	4	4-5
3% $FeSO_4$ + 4% Oxalic acid (IO3)	-6.66	-5.03	9.72	1.60	10.83	12.81	3-4	4-5
5% $FeSO_4$ + 4% Oxalic acid (IO5)	-4.64	-4.42	11.06	3.03	11.52	12.79	4	4-5

The results of color measurements are presented in Table 1. Samples dyed in the absence and presence of mordants are presented in Table 2 comparatively with the non-dyed sample (control). Figures 1-2 illustrate the changes in brightness, saturation, hue and color, as well as differences in color fastness.

Table 2. Samples dyed using extracts of *P. americana* berries, in the absence and presence of mordants compared to control (non-dyed sample).

	Methods			
	Exhaustion		Ultrasound-assisted	
Mordant	3%	5%	3%	5%
Control (non-dyed)				
Reference sample (dyed without mordant)				
Citric acid (CA)				
Tannic acid (TA)				
$FeSO_4$				
$CuSO_4$ + Oxalic acid				
$FeSO_4$ + Oxalic acid				

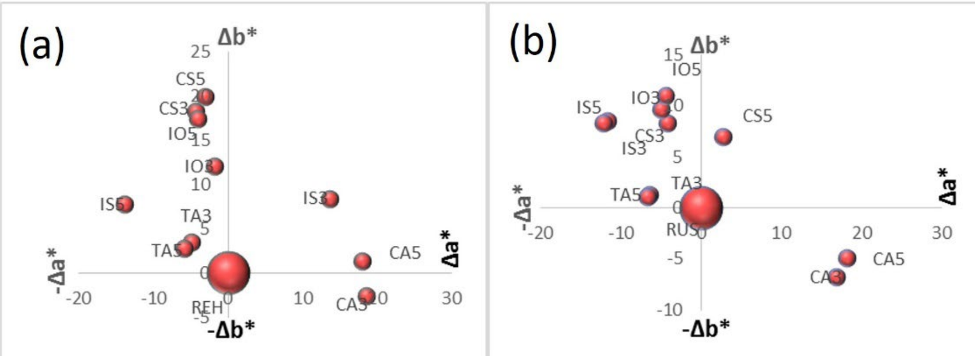

Figure 3. Distribution of CIELAB parameters of simultaneously mordanted and dyed samples, through the (a) conventional-exhaust procedure, and (b) ultrasound-assisted procedure

The color of wool fabrics dyed with pokeberry extract changes through a varied range from fuchsia-slightly reddish-purple-orange colors, through the addition of classic mordants or biomordants (Figure 3). The main betalain compound of pokeweed berries, prebetanin, possesses sulfonic groups, carboxylic groups and hydroxyl groups, which favored dyeing with citric and tannic acids, resulting in more intense coloration that leads to darker fuchsia-pink shades (Alshamar et al., 2022). Large differences in color and saturation, even tones over 6 units, were noticed in samples treated with citric acid at both concentrations 3% and 5%, $FeSO_4$ 3% and 5%, and $FeSO_4$ + oxalic acid, under conventional dyeing through exhaustion. Instead, by using the ultrasound-assisted method, the dye shades were kept closer to the reference, when using $CuSO_4$ + oxalic acid.

The present study focused on a conventional dyeing procedure with P. americana berries at 80°C, which was selected based on the wool dyeing standard procedure reported at 98°C (Ferrero & Periolatto, 2012). Acid dyes are most commonly used for wool fabrics (Fisher, 2025) being applied in the dyeing process at temperatures of 80-90°C for an optimal fixation to complete exhaustion (Cardamone & Damert, 2006).

Previous research of Liu et al. (2014) on wool fabrics dyed with Phytolacca berries (the exact species was not specified) reported that some of the pigment types degrades at temperatures above 60°C, thus causing a decrease of dyeability up to 70°C. On the other hand, Baaka et al. (2019), carried out a study on dyeing wool yarns with fruits extract of Phytolacca americana L. in a temperature range between 30°C and 90°C under different conditions of pH and time, reporting that optimum results were obtained at 90°C, pH 2, for 45 minutes.

The samples treated with citric acid kept the fuchsia-purple-orange color with positive a*(redness) and negative b*(blueness) coordinates, when dyeing by conventional procedure. The use of tannic acid slightly changed the hue towards pink-purple. Instead, for yellow-beige-light greenish shades, negative a* (greenness) and positive b* (yellowness) coordinates were found in samples treated with 5% iron sulfate, and copper sulfate, iron sulfate and oxalic acid (3 and 5%), as well.

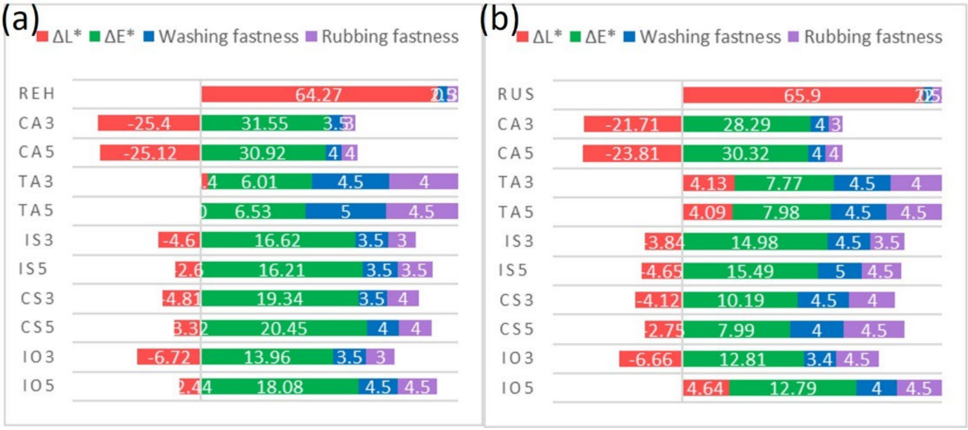

Figure 4. Effect of mordant concentration on luminosity, color and fastness values of samples dyed with *P. americana* fruit extract, (a) conventional technology; (b) ultrasound-assisted method (ΔL*- the difference in brightness, ΔE*- the total change in color)

The brightness of the samples slightly increased in samples dyed by mordanting with tannic acid using the ultrasound-assisted dyeing and remained approximately at the same values in samples conventionally dyed. The highest difference (ΔL*) and the decrease of the brightness were found in samples treated with 3% or 5% citric acid, the dye fixing stronger to the textile support and coloring the samples reddish-fuchsia (Table 1 and Figure 4). The resistance to light washing and dry rubbing increased by approximately 0.5-1.5 points through the addition of mordants. This is explained by the ability to bind and form a complex by coordinating the metal with the natural dye (Baaka et al., 2019; Adeel et al., 2018).

Regarding the use of biomordants (citric and tannic acids), the concentration of 5% proved acceptable when evaluating the color changes and the resistances of the dye, irrespective of the applied dyeing method. However, the results seem effective in case of using copper sulfate and ferrous sulfate, under conventional dyeing. Unlike other natural dyes, the fruit aqueous extract of *P. americana* showed appreciable color differences, the shade changes being significantly (reddish-pink-purple-orange tones) when using mordants mainly in the conventional dyeing process, and less under ultrasound-assisted conditions (Zhao et al., 2014).

The color of the dyed wool samples was stabilized when dyeing was performed in the presence of 3 and 5% biomordant concentrations, using both techniques, subsequently tested for the evaluation of in-service resistances, of 3.5 – 4 – 4.5 on the gray scale, according to specific standards.

CONCLUSIONS

Following the investigation into the dyeing potential of *P. americana* fruits, in the presence and absence of (bio)mordants, the following conclusions can be made:

- ATR-FTIR analysis of wool fibers confirmed the presence of key functional groups in dyed samples using conventional and ultrasound-assisted methods, without significant changes in the presence of mordants;
- *P. americana* dye adheres to wool fibers primarily through ionic bonding with carboxyl groups, along with secondary interactions like hydrogen bonding;
- shades of fuchsia-pink of eco-dyed wool samples were obtained when meta-mordanted with citric and tannic acids, through conventional and ultrasound-assisted dyeing methods;
- purple-orange-beige shades were obtained in eco-dyed wool samples treated with classic mordants based on iron and copper, and pink in samples dyed in the presence of oxalic acid;
- relatively good color strength properties of eco-dyed wool samples were found in the presence of biomordants such as citric or tannic acids; classic mordants added in concentrations of 5% showed values of 4 and 4-5 under conventional dyeing and ultrasound-assisted;
- good resistance of eco-dyed wool samples to light washing and dry rubbing was found, showing an improvement of up to 1.5 points on the gray scale.

Our results point out the promising biomass pigments extracted from *P. americana* dark red fruits to be further researched for developing sustainable and safe products intended for various applications including medical, by using friendly technologies of dyeing.

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50. ACTUAL TASKS ON AGRICULTURAL ENGINEERING

Original scientific paper

BIOSYNTHESIS OF LACCASES IN LIQUID AND SOLID MEDIA BY SOME MEDICINAL EDIBLE BASIDIOMYCETES

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ABSTRACT

Laccases are oxidoreductases increasingly used for the decomposition of lignocellulosic material in the treatment of agro-industrial and forestry by-products, for biodegradation of waste, toxic and xenobiotic compounds in the environment, for various purposes in obtaining biogas and bioethanol, in the food, pharmaceutical, textile industries, and analytical applications. In this research, the biosynthesis of laccases by 6 species of basidiomycetes was studied, namely: Pleurotus ostreatus, Polyporus squamosus, Lentinula edodes, Ganoderma lucidum, Flammulina filiformis, and Hypsizygus tessellatus. These mushrooms were tested for laccase production through a semi-quantitative screening method, and the highest values were determined for P. ostreatus which had a laccase index of 4.2, and G. lucidum with an index of 1.67. The lowest values of laccase activity were found in the glucose-yeast extract medium, ranging between 2.7 and 3.2 UmL^{-1}, and the highest values were found in the molasses and mineral salt culture, in which P. ostreatus produced laccase with an activity of 10 UmL^{-1}. In the solid medium with wheat grains, the laccase activity values had insignificant values, ranging between 1.2 and 2.0 UmL^{-1}.

Keywords: *biodegradation of polutants, laccase biosynthesis, submerged culture, solid state fermentation*

INTRODUCTION

Laccases (EC 1.10.3.2, p-diphenol: dioxygen oxidoreductase) are versatile enzymes, capable of degrading a wide variety of substrates such as phenolic and aromatic molecules (ortho- and para-diphenols, amino phenols, methoxy phenols, polyphenols), aliphatic amines and inorganic cations (Dana et al., 2017). Laccases are characterized by low substrate specificity, which gives them the ability to act on a wide variety of chemical compounds, which they decompose with the formation of water as a by-product through the reduction of molecular oxygen (Iark et al., 2019; Zhang et al., 2020).

These enzymes are also called “green catalysts” (Arregui et al., 2019) due to their properties of transforming various hazardous compounds from water and soil into less hazardous substances, considering that the production and accumulation of waste in human society has undergone a sharp increase in the last 50 years. In addition, laccases can degrade lignocellulosic material, making it more accessible for other subsequent transformations, such as those used in obtaining biogas or bioethanol.

Also, in recent times, the use of these enzymes has become increasingly known in various fields such as the food industry (used to obtain pectin, clarify vegetable and fruit juices and stabilize wines), the paper and pulp industry (for delignification of pulp, deinking of paper), the textile industry (fiber biobleaching, denim washing), various biosynthesis reactions of polymers and nanoparticles, as well as pretreatment processes of lignocellulosic material (Debnath et al., 2020).

The use of laccases has become increasingly widespread in the treatment of waste resulting from industry and agriculture, in the decolorization of dyes in the textile industry, the degradation of pesticides and other xenobiotic substances, the degradation of waste resulting from the consumption of medicines and cosmetics, as well as other highly hazardous compounds.

Fungal laccases

Laccases are produced by plants, bacteria and fungi. Fungal laccases act on various substrates in the environment such as phenolic compounds, aromatic amines, drugs, dyes, polyaromatic hydrocarbons (Polak, 2012). Fungi and bacteria synthesize laccases that decompose lignocellulose in the environment and are thus involved in the biogeochemical cycle of carbon. As secondary metabolites, laccases play a role in the process of cell protection, in sporogenesis, synthesis of specific pigments, decomposition of the lignocellulosic substrate to release nutrients necessary for the cell. In the soil, fungi that synthesize laccases are involved in the processes of litter decomposition and humification.

Laccases are produced mainly by fungi belonging to the phyla of Ascomycota, Basidiomycota, Chytridiomycota, Zygomycota and Oomycota, in association with the other two enzymes of the oxido-reductase class, namely lignin peroxidase and manganese peroxidase. The most high-producing fungal species among Basidiomycetes are *Agaricus bisporus, Pleurotus ostreatus, Lentinula edodes, Ganoderma* sp, *Phlebia radiata*, *Trametes versicolor,* and the Ascomycetes *Trichoderma* sp., *Chaetomium thermophilum*, *Theiophora terrestris* (Haq et al., 2021; Nasrin et al., 2022; Rajagopalu et al., 2017). Fungal laccases are usually produced as extracellular enzymes necessary for the formation of nutrients from lignocellulosic substrates, but there are also intracellular forms of laccases in some wood-degrading fungi (Maciel et al. 2013; Arregui et al. 2019).

Biosynthesis of laccases

Laccases are synthesized by fungi at the end of the exponential phase and in the stationary phase of growth, generally by secondary metabolism. For the biosynthesis of laccase, several successive steps are required, which refer to: 1) isolation and selection of fungal colonies with high productive potential (from different lignocellulosic substrates such as decayed wood, tree barks) by spread-plate or streak-plate technique followed by a screening method on specific media containing a chromogenic substrate such as ABTS, catechol or guaiacol; 2) testing of selected strains and establishment of optimal culture media; 3) testing of cultivation parameters, i.e. biosynthesis time, temperature, pH, nutrient concentration, volume and age of inoculum, aeration, enzyme inhibitors or activators, and others; separation and conditioning of the enzyme preparation as well as its characterization.

This paper aims to study the biosynthesis of laccases by edible medicinal mushrooms from the phylum Basidiomycetes, in submerged cultures or on solid media.

MATERIALS AND METHODS

Biological material and culture media

The laccase study was carried out using 6 strains of edible mushrooms from the phylum Basidiomycota belonging to the species *Pleurotus ostreatus* (oyster mushroom), *Polyporus squamosus* (dryad's saddle), *Ganoderma lucidum* (Reishi), *Flammulina filiformis* (Enoki), *Hypsizygus tesselatus* (Shimeji), and *Lentinula edodes* (Shiitake), known for their cultivation on lignocellulosic substrates.

These were cultivated in tubes or Petri dishes on Potato Dextrose Agar medium for maintenance and preservation at 4 °C and for obtaining stock and working cultures. The evidence of laccase biosynthesis was carried out on Potato Dextrose Agar medium supplemented with 0.02% guaiacol. Laccase biosynthesis was carried out both in liquid media in submerged cultures (SC) and in the solid state fermentation (SSF) system. For SC, 3 liquid culture media were used, namely: M1: glucose 20 gL^{-1}, yeast extract 3 gL^{-1}, $(NH_4)_2SO_4$ 2 gL^{-1} (Elisashvili, 2012); M2: glucose 10 gL^{-1}, yeast extract 10 gL^{-1}, peptone 10 gL^{-1}, $CuSO_4$ 0.5 mM (Tinoco et al., 2011) and M3: sugar beet molasses 100 gL^{-1}, NH_4NO_3 3 gL^{-1}, $(NH_4)_3PO_4$ 1 gL^{-1}. For the cultures in the SSF system, sterilized wheat with a humidity of 40% was used – M4.

The growth of cultures in liquid media was carried out in Erlenmeyer flasks containing 200 mL of medium, on a Gerhardt Thermoshake rotary incubator, at a temperature of 25 °C, 150 rpm, for 7 days. Cultures on wheat grains were grown in 500 mL Erlenmeyer flasks, on a quantity of 100 g of substrate with a humidity of 40%, for 10 days. All samples were analyzed at the end of development of the fungal mycelium in the culture filtrate or in the aqueous extract (extractio ratio 1:4) from the solid medium.

Microscopic observations were done using a Bel Photonics microscope.

Enzyme activity testing

Screening method for enzyme activity testing

Around the laccase-producing fungal colonies, guaiacol turns reddish brown due to the oxidation reaction catalyzed by the synthesized laccase which diffused into the medium.
The enzyme indices were calculated according to the formula:

$$I_E = \frac{Zone\ diameter}{Colony\ diameter} \quad (1)$$

Guaiacol assay method for laccase activity

A method based on the oxidation reaction of guaiacol in the presence of laccase, with the formation of a reddish brown coloration, was used.

Guaiacol can be used as a hydrogen donor (substrate) in the assay of laccase. Upon oxidation, it forms tetraguaiacol with a molar extinction coefficient $\varepsilon = 12100\ M^{-1}cm^{-1}$.

The reaction mixture consisted of:

- 1 mL Guaiacol 2 mM solution;
- 3 mL sodium acetate buffer 10 mM;
- 1 mL enzyme.

A control without enzyme was prepared for each type of culture medium.

The reaction mixture was incubated at 30 °C for 15 minutes and then the absorbance was read at 450 nm in a UV-Vis spectrophotometer UV-Vis T92+PG INSTRUMENTS.

1 enzymatic unit (U) was defined as the amount of enzyme required to oxidize 1 µmol of guaiacol per minute. Enzyme activity was calculated according to the formula (Isik et al., 2023):

$$\text{Laccase activity (LA)} = \frac{Abs \times Vol \times DF}{\varepsilon \times t \times v} \quad (2)$$

where:

LA = Laccase activity
A = Absorbance 450 nm
V =Total mixture volume (ml)
v = enzyme volume (ml)
t = incubation time
ε = Guaiacol [12100 M^{-1} cm^{-1}] molar absorption coefficient.
DF = dilution factor.

RESULTS AND DISCUSSION

The 6 selected basidiomycete species were first tested for the enzymatic index value through a screening method on a guaiacol-containing medium. The results obtained are presented in table 1 and figure 1. All the colonies grown on this chromogenic medium showed laccase activity after 5-7 days of growth at 25 °C. The most productive species were *P. ostreatus, L. edodes* and *G. lucidum*, which had an enzymatic index higher than 2.

The next stage of the study was the cultivation in Erlenmeyer flasks in submerged culture (using M1, M2, and M3 media) or in SSF system (M4 medium) and the analysis of enzymatic activity by the guaiacol method by determining the absorbance at 450 nm. These stages are shown in figure 2.

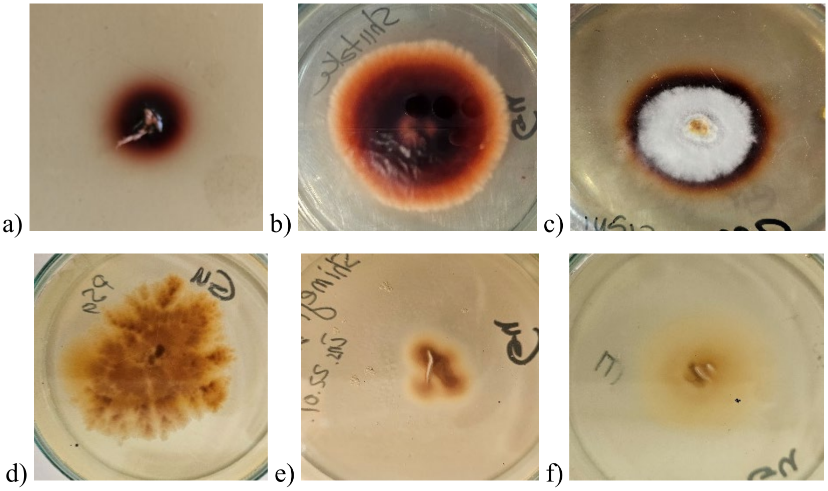

Figure 1. Laccase indices for the colonies of **a)** P. ostreatus; **b)** L. edodes; **c)** G. lucidum; **d)** P. squamosus; **e)** Hypsizygus tesselatus; **f)** F. filliformis

Table 1. Enzyme index values in PDA medium with guaiacol

Fungal species	**Laccase index (zone diameter/colony diameter)**
Flammulina filliformis	2.9/2.1
Lentinula edodes	1.7/0.7
Ganoderma lucidum	1.5/0.6
Pleurotus ostreatus	2.1/0.5
Polyporus squamosus	3.5/3.5
Hypsizygus tesselatus	5.4/6.5

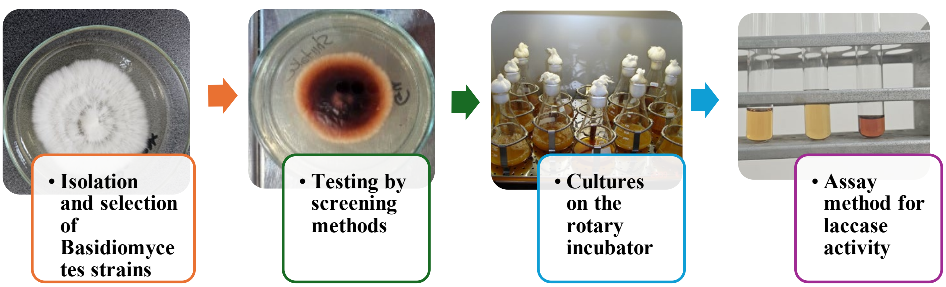

Figure 2. The main steps of the laccase biosynthesis process

The enzymatic activity values in the culture filtrate demonstrate that the tested edible mushroom species synthesize laccase better in liquid media, but weaker in the solid substrate used (wheat). The enzymatic activity was different depending on the composition of the culture medium (table 2). In the M1 medium, the laccase activity had the lowest values, although all species produced a significant amount of mycelial biomass. In the M2 medium, which, in addition to the carbon and nitrogen source, was supplemented with Cu^{2+} considered as an inducer, the laccase activity was higher than in the M1 medium, but the growth of three species, namely *P. ostreatus*, *Lentinula edodes* and *G. lucidum* seems to have been partially inhibited. The highest laccase activity values were recorded for the M3 medium with sugar cane molasses and mineral salts, for the *P. ostreatus* culture, for which the filtrate obtained had a value of more than 10 UmL^{-1}. In the solid medium with wheat grains, the laccase activity values had insignificant values, ranging between 1.2 and 2.0 UmL^{-1}.

Table 2. Enzyme activity values in SC and SSF media for the 6 edible mushroom species

Fungal species	**Laccase activity, UmL^{-1}**			
	M1	**M2**	**M3**	**M4**
Flammulina filliformis	-	1.9	2.75	0.01
Lentinula edodes	-	-	1.9	-
Ganoderma lucidum	2.75	-	4.54	1.9
Pleurotus ostreatus	3.2	4.3	10.5	1.2
Polyporus squamosus	-	1.8	2.0	1.9
Hypsizygus tesselatus	-	1.5	2.8	2.0

The results obtained demonstrated that these edible medicinal mushroom species can synthesize laccases in the culture media also used for obtaining mycelial biomass. After separation of this biomass, the culture liquid can be processed to produce enzyme preparations with laccase activity that can be used in the treatment of lignocellulosic materials, biodegradation of toxic pollutants in soil and water or other industrial uses.

Different species of basidiomycetes have been studied for laccase production. Among these, some of the most used were *Pleurotus ostreatus* and *Trametes versicolor* (Brugnari et al. 2018; Patel et al. 2018; Rouhani et al. 2018; Fathali et al. 2019; Wen et al. 2019). Other species that have been proven to produce laccases are *Agaricus blazei* (Valle et al. 2015), *Flammulina velutipes* (Wang et al. 2015), *Cerrena unicolor* (Zhang et al. 2018), *Ganoderma lucidum* (Palazzolo et al. 2019), *Lentinus tigrinus* (Sadeghian-Abadi et al. 2019).

Recently, numerous studies have investigated the biosynthesis of laccases under different cultivation conditions. Thus, Wang et al., 2016 obtained laccase with an activity of 14,902 UL^{-1} by cultivating the species *T. versicolor* in potato dextrose broth with vanillic acid as inducer. Pinheiro et al. (2020) cultivated *T. versicolor* in a stirred tank under static condition in a medium containing cotton gin waste and vinasse, synthesizing a laccase with an activity of 5000 UL^{-1}. Bettin et al., in 2020, used *Pleurotu sajor-caju* to obtain laccase in a stirred tank in culture media containing glucose, casein, benzoic acid and mineral solution, at different values of dissolved oxygen concentration.

CONCLUSIONS

The action of fungal laccases has become a remarkable biocatalytic tool increasingly used for the biodegradation of lignocellulosic materials and hazardous compounds in water and soil. Edible mushrooms from the phylum Basidiomycetes synthesize laccases along with mycelial biomass in SC and in SSF system.

Six species of edible medicinal mushrooms were tested regarding laccase production: *Pleurotus ostreatus, Polyporus squamosus, Ganoderma lucidum, Flammulina filiformis, Hypsizygus tesselatus*, and *Lentinula edodes*, which were cultivated in 3 liquid media and a solid substrate. The highest value of laccase activity was recorded by the species *Pleurotus ostreatus* in the M3 medium, containing molasses and mineral salts. In the case of the solid medium with wheat grains, the weakest enzyme production was obtained for all tested mushroom species.

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Review paper

CROSS-COMPETENCES IN AGRICULTURAL ENGINEERING: CURRICULUM DEVELOPMENT AND LIFELONG LEARNING IN THE CONTEXT OF RURAL DIGITIZATION

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ABSTRACT

Agricultural engineering (AgEng) is considered the technological backbone of agricultural production. Despite its importance to ensure agricultural production, it is currently a niche academic discipline that finds itself in competition with other academic domains of interest (DomInt) as biology, engineering or informatics. Pressure on AgEng as study programme has further mounted with the evolution of smart and precision agriculture (SmAgr), where digital technologies deeply interact with conventional agricultural technologies. Such new technological developments underline the need for interdisciplinary and cross-competences in AgEng education. Cross-competences such as mathematics, statistics, open-mindedness, multilingualism, databases or conceptual modelling integrate other DomInt's.

Cross-competences are necessary to fully understand problems and potentials of agricultural processes. On the basis of recently conducted surveys, this paper discusses the need for cross-competences twofold: through a rigorous approach to defining competence formation in the study of AgEng at higher educational level and through lifelong learning (LLL) opportunities that upskill already experienced engineers, technicians and agricultural practitioners.

The LLL perspective benefits from two recent ERASMUS+ projects that elaborated concrete AgEng educational programs with special focus on SmAgr technologies. The present paper discusses the development of academic AgEng *study programs and presents experiences and feedback on LLL training implemented in the above-mentioned projects. In particular, it examines how cross-competences are conveyed and how experience, expertise and cross-competences are brought together in order to address real-world tasks of AgEng.*

Keywords: *Agricultural engineering, smart agriculture, lifelong learning, engineering education, knowledge-worker, micro credentials*

INTRODUCTION

Climate change, global demographic developments and political crisis call for ever more efficient agricultural production systems. At the same time, contemporary agricultural production cannot simply intensify, but must produce environmentally, economically and socially sustainable (European Commission, 2023). Climate smart production is one approach, which relies heavily on the use of machinery and digital technologies proposed that is proposed by international organisations FAO, Worldbank and CGIAR.

This poses clear targets and challenges to the field of agricultural engineering (AgEng) to provide machinery and technologies that allow for highly efficient workflows at minimal environmental damage and resource use.

At the same time, EU agriculture has to deal with social and economic challenges that derive from structural labour shortage (Schuh, 2019). While SmAgr is widely diffused now in some areas as animal husbandry or in parts of intense crop farming, plentiful problems indicate that despite general motivation there is no frictionless transformation towards digital agriculture (Lowenbverg-Deboer and Erickson, 2019).

AgEng as academic discipline plays a pioneering role in the development of solutions in this respect. AgEng is the technical backbone of agricultural production (Lazzari and Mazzetto, 2016), its primary goal is providing technological solutions to sustainable biological production systems (Holden et al., 2020). The overriding objectives are the preservation of nature, the environment and the landscape. Central capacities of AgEng are the development of agricultural machines, technologies and production systems.

For the European Society of Agricultural Engineers, EurAgEng, "Agricultural engineering combines the disciplines of mechanical, civil, electrical and chemical engineering principles with a knowledge of agricultural principles according to technological principles. A key goal of this discipline is to improve the efficacy and sustainability of agricultural practices" (EurAgEng, 2023). Comparable conceptualizations are drawn in non-European contexts (ASABE, 2023; Singh, 2015).

The tools and skills to achieve these goals are partially provided by other engineering disciplines. Engineering and agriculture are highly dynamic professional and scientific sectors, not only since the emergence of digital technologies. The interdisciplinary character of AgEng has only increased with the digitization of the agrarian sector. SmAgr leverages advanced technologies to enhance efficiency, productivity, and sustainability by collecting and analyzing data for informed management decisions.

Ongoing rural digitization provides connectivity that enables the use of smart agricultural technologies as high-precision geo-localization, automated processes (e.g. steering, harrowing, harvesting, monitoring) or variable rate and precision pest management (FAO, 2022; VDI, 2021). However, the implementation of SmAgr cannot be compared with almost completely automated processes in industry, Industry 4.0, because we are in agriculture dealing with open, uncontrollable systems (Mazzetto et al., 2016). Rural digitization and subsequent implementation of SmAgr technologies is more complex as compared to the industry. Increasing production of knowledge, data and goods in agriculture must correlate with adequate farm size, human and natural resources, availability of specialised personnel. The gradual transfer of information technology SmAgr production processes entails, even on farm level, the decision of how to cope with these figures with regard to decision-making, without negatively affecting work organization or farm costs (Mazzetto et al., 2016).

This is a problem common to other production structures: in the industrial and tertiary sectors the progressive computerization of company procedures requests a new professional figure to support the actual company management. These so-called knowledge-workers (Drucker, 1993), whose role is to: (i) coordinate and manage the collection of company data; (ii) carry out intermediate processing and analysis with the production of summary information; (iii) provide for the production of documentation and distribution of information in the various sectors company, in order to implement the decision-making processes of the management sphere (Mazzetto et al., 2016).

In the European scenario, where increasingly few people work in agriculture, this scenario is intensified by SmAgr. Less persons, but better trained, must carry out control activities on higher levels. In this perspective, humans have to care for intellectually more advanced tasks, which require adequate competences (Mazzetto et al., 2020, 2016).

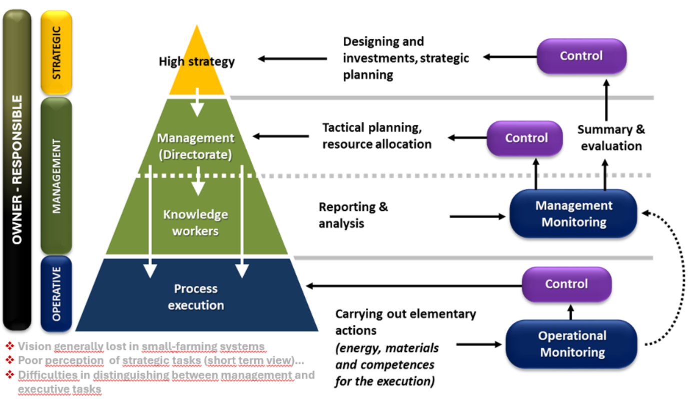

Figure 1. Control and decisional levels (Mazetto et al. 2020)

Figure 1 displays the hierarchical pyramid of control and decisional levels in agricultural production processes, which was elaborated earlier. The attributes of control activities lie in different decision-making domains (adapted from (Amber and Amber, 1962)). The management of any type of process by an agent requires that the agent must possess certain ‘attributes’, both physical and intellectual work at different application intensities, in a complementary relationship with each other. While at lower level, process execution, a certain amount of physical labour is required, this effort increasingly gives way to intellectual intensity. Rather little control activities can be automated, only human agents' guarantee the full scale of the 10 attribute levels. Automation can be defined as the set of technologies required to realize 'artificial agents' capable of replacing one or more human attributes in performing a task. In this sense, even simple mechanization can be understood as the lowest level of automation.

In the context of rural digitization and SmAgr, what are the learning and knowledge tasks for engineers, knowledge-workers and other stakeholders? How must the education and formation of engineers and knowledge-workers change in order to prepare for these new tasks in agriculture? The present article looks into educational aspects that the digital transformation poses to the discipline of AgEng.

MATERIALS AND METHODS

For this paper we scrutinize recent data on the use of digital technologies in agriculture that has been collected in surveys conducted in master thesis or research projects (Dorok, 2024; Gabriel and Gandorfer, 2022; Maiulini and Marraccini, 2024; Sebald, 2024). The surveys range from small numbers of participants to almost 1000 respondents and focus on the uptake and use of digital technologies in agriculture. The technological focus is primarily on plant production. In this study we take mainly a qualitative approach to the surveys and extract information regarding advantages and drawbacks in handling SmAgr technologies to understand which forms of upskilling would inform users and producers of such technologies alike.

The surveys confirm that digital technologies are used in agriculture, about 60% of the respondents use at least some tools (Gabriel and Gandorfer, 2022; Maiulini and Marraccini, 2024). Main technologies that are in use are guiding assistance, recording and documentation tools as well es variable rate equipment (Gabriel and Gandorfer, 2022; Maiulini and Marraccini, 2024). For the logic of scale, these technologies diffuse primarily on most productive areas of medium or big size, so that the return of investments is guaranteed in short time.

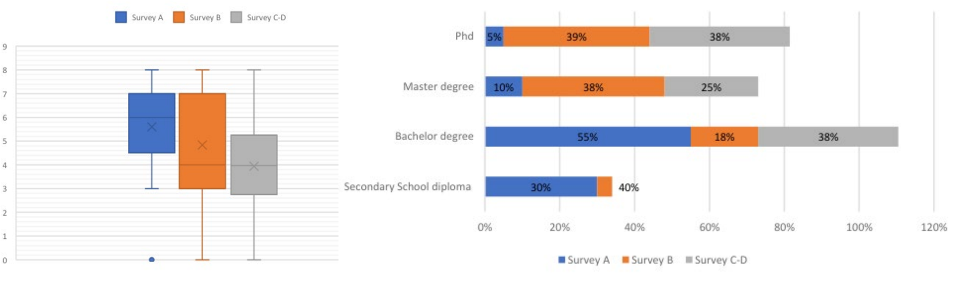

Figure 2. The ease of using technology in SmAgr, with 0 extremely complex and 9 very simple. The different surveys represent different stakeholders in agricultural production: a) Farmers, landowners, contractors, producer's associations, b) Dealers and manufacturers, c) Entrepreneurs and manager (Gabriel and Gandorfer, 2022).

Some technologies, as weather and trading forecast models or automated steering are most widely used (Gabriel and Gandorfer, 2022). Nevertheless, the survey data indicates also that the use of digital technologies is considered problematic.

Interestingly, the data displayed in fig. 2 provides information on the educational background of respondents. The ease of using digital technologies differs among diversely educated operators. Personnel with a longer educational career tends to use such technologies with more ease, as through educational institutions, they possess longer experience with technologies. Competences in SmAgr in the European context depend also on the age of practitioners and the respective farm size this person takes care of. Sebald (2024) reveals that respondents above 40 years were less inclined and optimistic to invest in SmAgr technologies, while 60,7% of respondents considered their "Operation too small" (p.53) and therefore abstain from investments.

The different backgrounds of users, managers and owners result in a feeling of unease regarding smart technologies. More than 65% of respondents in the Maiulini and Marraccini survey stated that they had received no or insufficient introduction to SmAgr technologies (2024, p.14). Barriers in the use of technologies result from a lack of the right learning opportunities. Adding to the plenty reasons why technologies are not taken up by practitioners, as costs, age, compatibility, connectivity, adequate education is also factor (Maiulini and Marraccini, 2024).

Respondents named different sources where to inform themselves about new technologies. In Europe, a major source of information are producer magazines, and, to a slightly lesser extent, colleagues and neighbors (Sebald, 2024). Both sources can not substitute proper training, but provide an informed entry into the topic. With regard to the topics of SmAgr for which additional upskilling is requested, Dorok draws the following ranking from a series of expert interviews:

1. Section control application
2. Automation of equipment/ implements
3. Digital management systems (FMIS)
4. Yield mapping
5. Near-infrared systems (NIRS)
6. Camera technology
7. Sensors and telemetry (Dorok, 2024).

Regarding education, practitioners, who already possess experience of SmAgr technologies, make some interesting points. Diverse statements are linked to the lack of skills that prevent the use of advanced technology. Repeatedly, missing user friendliness and too complicate technologies are mentioned (Gabriel and Gandorfer, 2022; Maiulini and Marraccini, 2024; Sebald, 2024). Sebald summarizes: "The main criticism, with around 50% of the European participants, is the required high-level technical understanding of smart farming technologies. Further, insufficient user-friendliness and no available support were mentioned by around 20%." (2024, p.64). These findings urge the industry to provide better user interfaces, while pointing to a better educational and training system around SmAgr technology too.

CROSS-COMPETENCES IN AGENG HIGHER EDUCATION AND LLL PROGRAMS

The above data clearly indicates the need for adequate education and training in AgEng, especially in SmAgr technologies. We have argued elsewhere (Mandler et al., 2023), the development of cross-competences appear a validate approach in both, education and training. With regard to academic research and education, cross-competences are necessary to fully understand problems and potentials of intertwined AgEng-processes, especially to foster a broad understanding of real-world problems (Johri, 2023; Walther et al., 2011). Cross-competences encompass a combination of knowledge, skills, and attitudes that enable a person to perform tasks effectively in a given context. Competences such as mathematics, statistics, open-mindedness, multilingualism, databases or conceptual modelling allow for a better understanding of a problem and subsequent finding of a solution. The specialization on requested competences can be organized with little organizational efforts in short time. Within AgEng education, cross-competences fulfil the important task of preparing students for social, scientific and ecological dimensions attached to modern digital agriculture, which prevents from negative overspecialization.

It has already been established above that the transfer of cross-competences in the realm of LLL can take place in a targeted and timely manner. Two recent ERASMUS+ projects transferred the approach of flexible upskilling for experienced engineers, technicians and agricultural practitioners and offered concrete training programs and modules around SmAgr technologies (USAGE, 2023). Within the projects, specific LLL opportunities on SmAgr technologies were developed, tailored to agricultural engineers and practitioners (Vidric et al., 2023). The projects conceptualized cross-competences through educational LLL products, such as modular courses, singular modules and drafted micro-credentials. Among USAGE partner universities, various mobile LLL courses of various size (European Credit Transfer and Accumulation System, ECTS) were realized:

- Smart Farming Technology, 1st level Master ", 60 ECTS
- Advanced Technologies in Smart Crop Farming, 10 ECTS
- Introduction to Smart Agriculture Technologies for Mountain Ecosystems, 3 ECTS
- Smart Farming & IOT in Agriculture, 8 ECTS.

The design of courses and modules was as flexible and mobile as possible (online/in person, or synchronized/asynchronous), in order to reach out to agricultural practitioners that were not able to attend centralized courses. All courses were run on particular educational web platforms. Despite the high level of mobility and flexibility, most courses faced problems to find adequate and sufficient participants. Planned courses had to be cancelled or where unable to be repeated. Many participants had an engineering or agricultural background and were between 20-50 years old. As to expect in LLL, educational levels and working experiences varied a lot, as well as the professional orientation of participants. A majority desired a future role in agriculture, which would fit in the frame of knowledge-worker. A knowledge worker is a professional whose primary role is to generate, apply and share knowledge for the benefit of an organization (Drucker, 1993; Vogler, 2024). These are persons who setup and run SmAgr technologies and conduct control and decisional tasks as outlined above. A smaller group of course participants oriented towards industry and used the courses to sharpen their professional profile at the intersection of agriculture and engineering.

While the mentioned training offers in the volume of 3-10 ECTS remained in the conventional structure of university teaching, USAGE brought forward the development of micro-credentials as innovative and fast way for learning (Council of the European Union, 2022; Paulus et al., 2022). A micro-credential is proof of the learning outcomes achieved following a short learning experience. Micro-credentials that range between 0,5-3 ECTS fit ideally for the purpose of transmitting cross-competences. Although, currently in Italy and elsewhere, its unclear regulatory status and recognition prevents their implementation (Maiulini and Marraccini, 2024). Thus, micro-credentials were not fully integrated in LLL programs, but conceptually drafted. Micro-credentials are ideal for the aforementioned cross-competences, as they can react immediately to the requirements of new technologies.

The experiences from both USAGE projects underline how innovative LLL approaches, as micro-credentials, and flexible learning modules can successfully teach cross-competences in AgEng and SmAgr as stand-alone topics. LLL modules of less than 1 ECTS on topics i.e. global navigation satellite system (GNSS), software, sensors or machine safety were of high request as these are useful also outside the field of AgEng. Such cross-competences provide benefits to knowledge-workers with mixed educational background, but who possess lots of experience and competences. In the agricultural sector, where only a minority of professionals attended higher education institutions, but is confronted with complex technologies, these learning opportunities are an incentive to integrate the own curriculum with particular capabilities.

RESULTS AND DISCUSSION

The importance of cross-competences in agriculture is increasing, particularly due to the spread of SmAgr technologies. Cross-competences help engineers and practitioners to comprehensively understand problems and find adequate solutions. In academic engineering education, cross-competences are integrated in advanced AgEng curriculum to provide a complete formation that covers social, agricultural and engineering domains. Engineering competence as multidimensional construct, is as such subject to change and updates. With cross-competences, eventual updates within a stable curriculum on bachelor and master level, are easily doable. Emerging SmAgr technologies require intense interdisciplinarity, thus incentivize to strengthen and modernize the curriculum of AgEng. The discipline often suffers the competition with experts from other domains; which is normal when a domain is open to interdisciplinary approaches. The focus needs to remain on the primary goal, i.e. remaining the technological backbone of biological production systems, determining the exact role and contribution of each actor in AgEng processes.

We argue, that the provision of cross-competences is equally important to upskill the existing agricultural labour force, e.g. knowledge-workers, especially in the context of rural digitization and SmAgr technologies. Integrating cross-competences into special LLL activities for SmAgr can be done via modules or micro-credentials, which can be designed in a very targeted manner. Experiences from the Erasmus+ projects showed options how to upskill parts of the agricultural labour force, e.g. knowledge-worker. While projects still relied heavily on complete courses, experience showed that single modules and potential micro-credentials can cause high attraction. In any case, it is worth to reflect on the concept of cross-competences in AgEng in order to restructure thematic blocs and review didactics. It remains a challenge in engineering education that certain topics cannot be divided into arbitrarily small units. Thus, it is important to understand the limits for cross-competence modules in LLL programs: they can contribute to AgEng concepts and skills, but not substitute expertise themselves. This is eventually the challenge for AgEng LLL programmes: on the one hand, the modules should teach skills, on the other hand, they must be adapted to the level of the respective participants. This regularly leads to problems in the engineering sciences. Cross-comp modules have to draw a fine line here, which leads to SmAgr technologies.

Despite clearance regarding education, LLL and cross-competences has increased, there remain some open tasks. For the vision of a general digital upskilling of the agricultural labour force, some overarching difficulties remain. One is surely the incomplete digitization of rural infrastructures, which slows down the diffusion of SmAgr technologies. This concerns often non-favourable agricultural areas with smaller farm structures. This group remains difficult to reach. Here, some extra efforts are required form governments and industry to advance rural digitization. Beside that, AgEng education and the industry must move forward to a better understanding of agricultural working processes to ease the use of technology, increase reliability of technologies and its user-friendliness.

CONCLUSION

The paper discussed how the AgEng academic curriculum should be constructed to cope with demands of SmAgr. To realize best educational results, the integration of cross-competences is important as students learn to comprehend problems and solutions in a broader way. Providing lifelong learners with cross-competences is equally important. Lifelong learners derive from different educational backgrounds. In the context of rural digitization and SmAgr technologies, cross-competences can close knowledge gaps. The paper discussed the advantages that modules on cross-competence provide, first and foremost to upskill various agricultural practitioners in a timely, short and precise manner.

On the one hand, the agricultural workforce will learn to deal with the speed and development of smart tech and the further automation and robotisation of agriculture. On the other hand, AgEng as a discipline will be able to develop far-reaching visions for technologies in productive biosystems.

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50. ACTUAL TASKS ON AGRICULTURAL ENGINEERING

Original scientific paper

EVALUATING AGRICULTURAL MACHINERY EFFECTIVENESS USING CATBOOST MACHINE LEARNING

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ABSTRACT

Defining the optimal machinery for specific working conditions is crucial for successful agricultural production. The conventional concept of effectiveness, often determined using fuzzy set theory, is synthesized through indicators such as reliability, maintainability, and functionality. With extensive field data generated for different technical systems, artificial intelligence (AI) can significantly aid in developing complex models that accurately assess effectiveness. This study aims to demonstrate the potential of the CatBoost machine learning model in addressing these challenges. The results are expected to enhance the existing analysis database, improving system efficiency and extending the operational lifespan of technical systems, particularly tractors. The model was applied to three tractors from the same category, operating in the climate and soil conditions of the broader Belgrade area. Model training involved adjusting CatBoost parameters, focusing on loss functions. With the LogLoss function, total model loss reached 0.001702, and for the MultiClass function, the loss was 0.00105, demonstrating that the applied machine learning model can reliably assess tractor effectiveness.

Key words: *Machine learning, CatBoost algorithm, tractor performance, agricultural systems, predictive modeling*

INTRODUCTION

The agricultural sector, a backbone of global food production, is increasingly pressured to improve productivity and efficiency while addressing the environmental and economic challenges of sustainable production. Agricultural machinery, particularly tractors, plays a critical role in large-scale farming by optimizing field productivity and reducing labor demands. Given the rising global demand for food and agricultural products, selecting optimal machinery suited to specific working conditions is essential for efficient operations and sustainable management. As it was mentioned by Mileusnic et al. (2019), tractors, as primary power units in agriculture, are instrumental across various tasks, from soil preparation to harvesting, making their operational effectiveness a crucial factor that influences fuel efficiency, productivity, and overall farm profitability.

Evaluating machinery effectiveness has traditionally involved key indicators such as reliability, maintainability, and functionality, which together provide a comprehensive measure of performance. The synthesis of these indicators into a single measure, termed "effectiveness," enables more precise assessments of a machine's operational suitability under varying conditions. Fuzzy set theory, as highlighted in research Miodragovic et al. (2012), offers an analytical framework to assess effectiveness by handling the uncertainties inherent in agricultural environments, thus enabling a structured approach to evaluating machinery performance under variable conditions. However, the scale and complexity of data generated by modern machinery necessitate advanced analytical approaches beyond traditional methods.

The accurate measurement of productivity is not only essential for operational efficiency but also central to achieving sustainability goals. Cachia et al. (2018), emphasize that productivity, as a measure of the ratio of outputs to inputs, serves as a critical indicator of both economic performance and resource efficiency. Enhanced productivity allows farms to optimize resource use and increase income, directly supporting economic growth and resilience. This is particularly significant in developing regions, where productivity measurements are often hindered by data scarcity. Standardized and comprehensive measurement frameworks, as recommended by Cachia et al., are crucial for supporting consistent productivity improvements across agricultural systems.

Recent developments in artificial intelligence (AI) offer transformative tools for agricultural machinery management. AI-driven models allow for the analysis of large datasets, providing insights that enable the optimization of machinery parameters and accurate predictions of performance. Machine learning has emerged as a transformative tool in agriculture, enabling advanced data analysis and decision-making across various domains such as crop yield prediction, soil health monitoring, and machinery optimization, in Liakos et al. (2018). This review of machine learning applications highlights the broad potential of these techniques to address complex challenges in agricultural management, supporting the relevance of models like CatBoost in this field. It is known for its high accuracy in handling complex, categorical data, making it ideal for the agricultural sector. By processing diverse variables, such as soil type mentioned by Mana et al. (2024), climate, and equipment specifications, CatBoost enables a nuanced analysis of machinery effectiveness that is both comprehensive and adaptable to specific conditions.

In this study, CatBoost is applied to assess tractor effectiveness by analyzing data from tractors operating in the Belgrade region. Key performance metrics, such as reliability, maintainability, and functionality, were examined across different tractor models, providing insights critical not only for short-term productivity but also for the long-term sustainability of machinery use. These insights are intended to support informed decision-making in maintenance scheduling, equipment replacement, and investment in new machinery as described by different authors (Hamasha et al., 2023; Huang et al., 2019; Kapoor et al., 2023; Mileusnic et al., 2019).

The implementation of AI in this context is notably advantageous. Traditional models often rely on historical data and manual assessment, which can lead to less accurate predictions and higher operational costs. In contrast, AI models, like CatBoost, can process real-time data and adapt to environmental variations, thereby providing dynamic, accurate predictions that aid in minimizing downtime, reducing maintenance expenses, and extending machinery lifespan. By utilizing loss functions such as LogLoss and MultiClass, the CatBoost model in this study achieved high accuracy in predicting operational effectiveness, which emphasizes the practical benefits of machine learning in optimizing agricultural machinery management, in Santos Valle et al. (2020) and Zhao et al. (2024).

This research contributes to the growing field of sustainable agriculture by validating AI's potential in predictive maintenance and performance optimization. Through data-driven insights, this study provides a foundation for decision-makers and equipment manufacturers to make better-informed choices regarding machinery utilization, cost reduction, and sustainable practices, thereby fostering a more resilient and efficient future in agriculture.

MATERIALS AND METHODS

Study Area and Machinery Selection

This study focuses on evaluating tractor effectiveness using machine learning techniques. The research was conducted using field data collected from three tractors operating in the broader Belgrade area. These tractors, selected to represent similar operational capacities within the same category in Kapoor et al. (2023), were tested under local soil and climatic conditions to assess their performance in real-world agricultural applications.

Data Collection

Data was collected from field trials where the tractors were subjected to various operational tasks under consistent environmental conditions to ensure comparability. Operational parameters, including reliability, maintainability, and functionality, were continuously monitored. These parameters were chosen as key indicators of tractor effectiveness, reflecting both the tractors' performance and their suitability for sustained use in agricultural operations.

Machine Learning Model: CatBoost

The CatBoost machine learning model was chosen for this study due to its capability to handle complex data with categorical features efficiently. CatBoost, which stands for "Categorical Boosting," is a gradient boosting algorithm developed by Yandex. It is particularly suited for datasets with categorical variables, as it incorporates unique techniques for handling categorical data without the need for extensive preprocessing, as it is shown in Prokhorenkova et al. (2018), and Official CatBoost Documentation.

One of CatBoost's distinguishing features is its approach to encoding categorical data through *Ordered Target Statistics*, which minimizes the risk of target leakage—a common issue in machine learning where information from the target variable is unintentionally used in the training data, causing prediction biases. Unlike conventional methods, CatBoost uses permutations of data to avoid this shift, ensuring that categorical features do not use information from the same sample they are predicting mentioned by Vidhya (2017) and Ibrahim et al. (2020).

In addition to Ordered Target Statistics, CatBoost implements *Ordered Boosting*, a process that uses a randomized permutation of training data to improve model stability and reduce prediction shift, which occurs when the model's predictions for training samples deviate from those it makes on unseen data, shown in Zhao et al. (2024) and Prokhorenkova et al. (2019). These techniques not only improve the model's accuracy but also maintain consistency across varied datasets, which is crucial when analyzing agricultural data that often involves mixed data types and complex dependencies among features (Araujo et al., 2023; Zhai et al., 2023).

Model Training and Parameter Optimization

The CatBoost model was trained by tuning its hyperparameters to improve accuracy. Key hyperparameters included loss functions, which were optimized to reduce model error. For this study, the two primary loss functions used were:

1. *LogLoss* – optimized for binary classification tasks, with a final model loss of 0.001702.
2. *MultiClass* – suited for multi-class predictions, achieving a model loss of 0.00105.

Evaluation of Model Performance

The effectiveness of the CatBoost model was evaluated based on the accuracy of its predictions regarding tractor effectiveness. The low loss values for both LogLoss and MultiClass functions indicate that the model reliably predicted tractor performance. These results, by Zhai et al. (2023), demonstrate the model's potential for assessing operational effectiveness, particularly in determining tractor reliability, maintainability, and functionality in specific agricultural environments.

Database Expansion and Further Analysis

The data generated and processed through the CatBoost model contributes to an existing agricultural machinery performance database. This expanded database will serve as a valuable resource for further analyses, aiding in the improvement of agricultural machinery configurations, enhancing system efficiency, and extending the operational lifespan of technical systems in agriculture.

RESULTS AND DISCUSSION

Advanced machine learning techniques, such as convolutional neural networks presented in paper Kamilaris and Prenefeta-Boldu (2018), have shown considerable promise in precision agriculture, enhancing the ability to analyze complex environmental data and optimize crop management strategies. This aligns with our findings on the effectiveness of the CatBoost model for accurately assessing machinery performance under variable field conditions, highlighting the broader utility of machine learning in agricultural optimization.

The CatBoost model demonstrated exceptional predictive accuracy in evaluating the effectiveness of three tractor models (Tractor A, Tractor B, and Tractor C) operating in the Belgrade area. Based on linguistic assessments, three main effectiveness categories were analyzed: "excellent," "good," and "average," with ratings derived from reliability (R), maintainability (M), and functionality (F) scores for each tractor.

Model Performance Evaluation

The dual-parameter assessment of each tractor was based on values of reliability (R), maintainability (M), and functionality (F), as shown in Table 1.

Table 1. Assessment of Tractor Effectiveness Based on R, M, and F Parameters

Analyst	Tractor A	Tractor B	Tractor C
R	Excellent, Average	Good, Excellent	Average, Good
M	Excellent, Adequate	Good, Excellent	Adequate, Poor
F	Excellent, Good	Good, Excellent	Average, Good

Acceptable values for all categories are "excellent" and "good," which in the model yield a result of 1, meaning the tractor is considered reliable, while other values yield a result of 0, meaning the tractor is deemed unreliable as shown in Wei et al., 2024.

Based on the Analyst (R, M, F) values, the model produced good results, with *False Positive* and *False Negative* values equal to 0, except in the "Assessment" category. The differences between tractors in terms of reliability are presented in Table 2.

Table 2. Reliability Classification of Tractors Based on True Positive, False Positive, and False Negative Rates

Tractor	True Positive	False Positive	False Negative
A	95%	3%	2%
B	89%	7%	4%
C	78%	12%	10%

Tractor A showed the best results, while Tractor C had the fewest "excellent" ratings, resulting in a slightly higher rate of false positives. These results confirm the advantage of the CatBoost model in classification accuracy when target values are set as 0 and 1.

Parameter Tuning and Model Stability

In this study, two CatBoost models (Model 1 and Model 2) were tested to evaluate tractor effectiveness. Each model used different hyperparameters, specifically the number of iterations and learning rate, to optimize performance. The detailed training logs and outcomes for both models are outlined below.

Model 1:

- Iterations: 830 (stopped early due to the overfitting detector)
- Learning Rate: 0.016545
- Best Test Loss: 0.00206100402 at iteration 830

The training log for Model 1 is summarized in Table 3.

Table 3. Model 1 Training Log Summary

Iteration	Learn loss	Test loss	Best test loss	Total time	Remaining time
0	0.6659452	0.6649347	0.6649347 (0)	3.18ms	3.17s
100	0.0393094	0.0416078	0.0416078 (100)	258ms	2.30s
200	0.0135107	0.0150988	0.0150988 (200)	390ms	1.55s
...	...	...	...	...	...
800	0.0017735	0.0021469	0.0021469 (800)	935ms	232ms
stopped by overfitting detector (50 iterations wait)					

Model 2:

- Iterations: 999
- Learning Rate: 0.102441
- Best Test Loss: 0.001163862437 at iteration 999

The training log for Model 2 is summarized in Table 4.

Table 4. Model 2 Training Log Summary

Iteration	Learn loss	Test loss	Best test loss	Total time	Remaining time
0	0.6145110	0.6145110	0.6145110 (0)	275µs	276ms
100	0.0143971	0.0155154	0.0155154 (100)	16.3ms	145ms
200	0.0059669	0.0065214	0.0065214 (200)	32.4ms	129ms
...	...	...	...	...	...
900	0.0011662	0.0012869	0.0012869 (900)	166ms	18.3ms
999	0.0010541	0.0011639	0.0011639 (999)	183ms	0us

The results from both models demonstrate high accuracy and model stability across iterations, with Model 1 reaching optimal performance at iteration 830 due to early stopping, while Model 2 completed all 999 iterations.

Both configurations yielded similarly high accuracy, with minimal deviations in R^2, Mean Squared Error (MSE), and Root Mean Squared Error (RMSE) metrics, as shown in Table 5.

Table 5. Performance Metrics for Model 1 and Model 2

Metric	Model 1	Model 2
R^2	0.99999	0.99999
MSE	6.71×10−166.71×10−16	6.71×10−166.71×10−16
RMSE	2.59×10−82.59×10−8	2.59×10−82.59×10−8

Although the models had different *learning rates* and numbers of iterations, they both achieved extremely high accuracy. The CatBoost model demonstrated stability and adaptability with parameter variations, as confirmed by Prokhorenkova et al., 2018 and Ibrahim et al., 2020.

The correlation heatmap for the variables used in the model is shown in Figure 1. This heatmap illustrates the relationships between the variables Tractor, Analyst, Assest, and P, highlighting significant correlations that contribute to the model's predictive accuracy.

Figure 1. Correlation Heatmap of Variables Used in CatBoost Model

Confusion Matrix

Table 6. Confusion Matrix of Tractor Reliability Prediction

Tractor	Predicted Reliable	Predicted Unreliable
A	95%	5%
B	89%	11%
C	78%	22%

The confusion matrix results indicate high accuracy for the CatBoost model, especially for *Tractor A*, which has the lowest rate of incorrect predictions.

These findings demonstrate the adaptability of the CatBoost model under varied operational conditions, aligning with previous studies that highlight machine learning's role in determining ecological suitability for agricultural machinery and crop management as explained in Chang et al., 2023 and Moshou et al., 2004.

Implications and Future Work

This study confirms that the CatBoost model provides a reliable assessment of the effectiveness of agricultural machinery. Next steps include expanding the dataset to include additional tractor models and operational conditions to further improve model generalizability and applicability as mentioned in Bechar et al., 2016.

CONCLUSION

The results of this study confirm that the CatBoost machine learning model is highly effective in predicting the operational effectiveness of agricultural machinery, specifically tractors, in real-world conditions. By leveraging key indicators such as reliability, maintainability, and functionality, the model demonstrated exceptional accuracy, as evidenced by the high R^2 values and minimal errors in both Model 1 and Model 2. The two models, with variations in learning rates and iteration counts, produced consistently high prediction accuracy, indicating the robustness and adaptability of the CatBoost algorithm for this application.

Model 1, with a lower learning rate, reached optimal performance at iteration 830 due to early stopping by the overfitting detector, while Model 2, with a higher learning rate, completed all 999 iterations and achieved a slightly lower test loss. Both models showed high consistency across performance metrics, suggesting that CatBoost's handling of categorical data and ordered boosting provides significant advantages in agricultural applications where diverse environmental and operational factors interact.

The implications of these findings are substantial for the agricultural sector. The high accuracy of the CatBoost model in assessing tractor effectiveness enables data-driven decisions regarding machinery maintenance, replacement, and investment, ultimately supporting more efficient and sustainable farming operations. This approach contributes to the broader goals of increasing productivity and reducing operational costs in agriculture.

Future work could expand on this study by including a wider range of tractor models and operational conditions to enhance model generalizability, as it was mentioned by Shobha Ajin et all, 2024. Additionally, incorporating real-time data and further refining the model parameters could further improve prediction accuracy, making CatBoost a valuable tool for long-term agricultural machinery management and sustainable practices.

ACKNOWLEDGEMENT

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50. ACTUAL TASKS ON AGRICULTURAL ENGINEERING

Original scientific paper

SUSTAINABLE DEVELOPMENT BASED ON REMOTE WORK AND ARTIFICIAL INTELLIGENCE

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ABSTRACT

Artificial intelligence (AI) is increasingly becoming a cornerstone in Romania's approach to sustainable development. Among the new elements of labor relations, remote work (RW) is in the attention of both researchers and the business environment. The modernization of agriculture currently consists of both the development of precision agriculture and the use of AI, according to the current level of knowledge. Starting from the realities encountered in companies regarding the use of remote work, this research refers to a study on how remote work is carried out, correlated with the economic efficiency of the companies corroborated with the level of well-being of teleworkers. It demonstrates the role that AI can play in monitoring the effectiveness of remote work structures, identifying bottlenecks, inefficiencies and potential areas for improvement. Neural models were used. Analyzing this data has resulted in greater knowledge and a deeper understanding of how different factors influence the use and level of satisfaction among employees with remote work. By integrating AI into strategies for using RW, not only in Romania, a more resilient, more efficient and sustainable future can be ensured both for businesses and for increasing the well-being of the workforce.

Keywords: *artificial intelligence (AI), remote work (RW), sustainability, precision agriculture*

INTRODUCTION

Analyzing Romania's sustainable development strategy from the perspective of the decision adopted by the 193 UN member states in 2015, greater concern is needed for the modernization of agriculture. Current technological progress can make a decisive contribution to achieving the first two main objectives, from the list of 17 established 10 years ago, ensuring a path to poverty reduction and eradication, while providing healthy and sufficient food for everyone (Sachs, 2024). This implies greater attention to the efficient and healthy use of agricultural resources. Knowing Romania's growing contribution to agricultural production (European Union, 2024), the strategy implementation agenda, ongoing until 2030, includes appropriate government measures with the main goal of ensuring decent working conditions for all people (Chandran, 2022).

For the present research on agricultural efficiency, considering that remote work (RW) is becoming a vital component of modern work environments (Tissandier and Mariani-Rousset, 2021), AI offers innovative solutions for monitoring, optimizing, and improving RW efficiency. In the context of RW, AI-based tools, such as neural networks and machine learning algorithms, are used to predict employee performance, streamline workflows, and maximize productivity (Mogoșanu, 2024). By analyzing patterns and providing real-time information, AI allows companies to make informed decisions, adapt their strategies, and ensure optimal resource allocation (Taboada et al., 2023). One of the critical contributions of AI in RW is its ability to refine organizational policies. Through advanced data analysis, AI can assess the effectiveness of remote work structures, identifying bottlenecks, inefficiencies, and potential areas for improvement. This capability not only leads to better management practices but also encourages a more resilient and flexible workforce (Adascalitei et al., 2022; European Union, 2023).

AI fits very well into the current issues of modern agriculture. This paper brings into focus the effectiveness that AI can determine in the use of RW. The research aims at the use of AI means in simulating the conditions of use of RW in relation to indicators of economic efficiency of the applying companies, respectively the degree of well-being of the employees.

MATERIALS AND METHODS

In general, the goals set for sustainable development are about the *5 Ps,* (Figure 1): *People, Planet, Prosperity, Peace* and *Partnership* (Cohrs, 2021). The naming of these five main directions gives the image of the dynamics of strategy implementation, in relation to the political-social evolution of society, as well as technological progress.

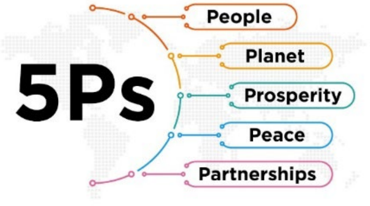


Figure 1. The 5 directions of action for sustainable development (Cohrs, 2021).

Scientific research in academia, constantly oriented towards solving societal problems, in the context of sustainable development, has included a significant expansion in recent years of the lucrative activity carried out under the RW regime (Solomon, 2021; Countoris et al., 2023).

In a first phase, in cooperation with other state institutions in Romania, extensive research was carried out on how to conduct RW under the existing legislation (Law no. 81, 2018), (Dita, 2021). The current experimental research is part of a larger project (Mogoșanu, 2024), based on a study sample of RW, comprising 634 tele-employees, from 22 companies in Timiș County (Romania).

To establish the conditions and research methods, the specialized literature was consulted, keeping in mind the need for a more nuanced approach to RW, considering factors that refer to the contextual conditions in which RW is carried out (for example, job design, social and physical environment of homework (Weber et al., 2022). It started from the observation of the undoubted trend of ensuring the continuity of efforts towards its acceleration, with the provision of an increasingly high-performance technological infrastructure, in compliance with an appropriate legal framework adopted (Loia and Adinolfi, 2021). The research falls within the EU strategy regarding the development of digitalization based on an adequate investment program to lead to better performance in a relatively short time (Stoica et al., 2021; Vargas et al., 2022).

Changes in mentality were taken into account, including those who work the land (Krakowiak-Bal, 2009), appreciating the opportunity for remote work (RW) that has emerged in the practice of large farmers, users of the precision agriculture (PA) system, with applications such as: data management (GIS), procedures for ensuring soil maintenance through variable-rate fertilization, diagnosing plant condition by tracking chlorophyll levels, for certain maintenance and product collection works, the use of collaborative robots, as well as other advanced mechatronic systems, advanced technologies based on wireless sensor networks that help reduce crop losses, prevent over-watering of crops and help increase the real yield of crops, etc. (Dzitac, 2023). The person coordinating the supervision of the automated sensor system intended for monitoring the crop field can exercise his duties remotely, using a wireless system for transmitting recorded data (Jyotshna Kumari and Kumar, 2017).

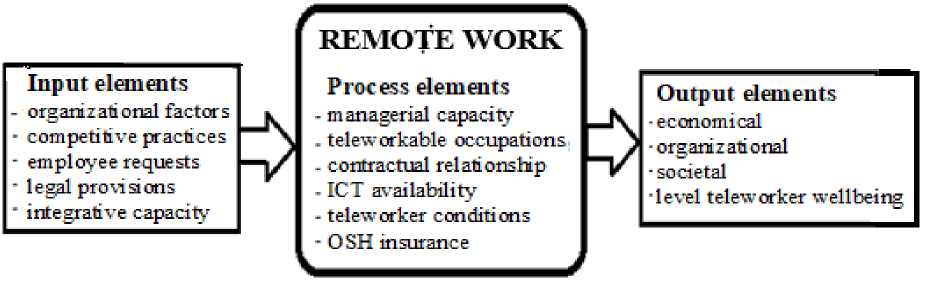


Figure 2. Scheme of the remote work (RW) system, (Mogoșanu, 2024)

To identify as many generic elements as possible, the RW relations sub-system, part of the general work relations system, was defined (Figure 2). Thus, RW is analyzed and evaluated as a whole, regardless of any intercepted exception points. Considering the previous considerations and the records identified in the specialized literature, several variables were established that were identified after consultation through a questionnaire addressed to employers, respectively another to employees. An essential condition of the consultation was anonymity.

For a more efficient exploitation of data resulting from experimental research, a neural network was developed for forecasting the profit in a company, under the conditions of the use of RW. As input and output variables for this neural network, the categories shown in Table 1, were set.

Table 1. The categories of input and output variables used in the construction of the neural network**.**

INPUTS FOR THE NEURAL NETWORK	
Category of input	**Detailed input**
Profit	X21 = Contribution of RW activity to work productivity and profit as percentage
Advantages appreciated from the perspective of the future expansion of RW	X31 = Economic advantages X32 = Social advantages X33 = Ergonomic advantages X34 = Advantages related to labor productivity X35 = Advantages in terms of OSH
Disadvantages felt by employers towards the RW system	X41 = Appreciation of the economic disadvantages X42 = Appreciation of the social disadvantages X43 = Appreciation of ergonomic disadvantages X44 = Appreciation of the disadvantages related to work productivity X45 = Appreciation of the disadvantages from the OSH perspective
degree of danger	X5 = The degree of danger by carrying out activities in the RW regime, compared to work at the headquarters.
accidents/ sanctions/ labor disputes/ negative aspects	X6 = Monthly average of accidents/sanctions/labor disputes/negative aspects/indiscipline, in the case of RW in relation to work at the headquarters
employer's intentions	X7 = The employer's intentions to expand activities under the RW regime.
Number of jobs / positions	X1a1 = Number of positions X1b1 = Number of full-time RW positions X1b2 = Number of positions under RW regime with partial contract X1b3 = Number of positions in the regime of occasional RW.
OUTPUTS FOR THE NEURAL NETWORK	
Category of output	**Detailed output**
productivity	Xprofit = productivity computed as average profit per telecommuter.

In the first phase, a synthetic analysis of multiple variables was performed, using *Statgraphics Centurion* as the statistical analysis method. This procedure was designed to summarize several columns of quantitative data.

The RW subsystem approach considers the dimensionality scale taken recently (Jahagirdar and Bankar, 2020). *AI* was used to anticipate the future values of the output variables, based on the information available from the questionnaires. Certain variables relevant to the problem were selected using data sets to develop appropriate neural networks. In general, neural networks are used in forecasts, when the data to be analyzed is complex and/or non-linear or when there are subtle dependencies between the input and output variables.

The neural network was built using the *Neural Fitting module of MATLAB*, a numerical computing framework and programming language developed by MathWorks, (Slavici, 2007). The opportunity offered by *the Neural Fitting Module* given by an intuitive graphical interface was used, through which it was possible to build and train neural networks without having extensive programming experience. This module allowed the design and training of a wide range of networks, using a wide range of state-of-the-art machines learning algorithms. Also, certain tools were used from this module that allow the performance evaluation of the constructed networks and data analysis, being used in the generation of neural networks for image recognition, natural language processing, temporal predictions, control of dynamic systems, but also for the creation of more accurate models than statistical models, including nonlinear regressions and simulations of complex phenomena (Tomoiaga, 2021).

Neural network training was done using the *Levenberg-Marquardt algorithm*. This optimization technique, developed by *Kenneth Levenberg and Donald Marquardt*, is frequently used in non-linear regression problems (Mogoșanu, 2024).

The purpose of designing and implementing this neural network was to predict the average profit per telecommuter, an essential aspect in optimizing organizational performance, offering the possibility of understanding with good confidence the existing relationship between the perceived advantages and disadvantages of RW and profit, human resource management, evaluating the effectiveness of the policy of RW, anticipating future trends and developing RW strategies.

RESULTS AND DISCUSSION

To study the profitable activity in RW correlated with the profit recorded by the company, the data resulting from the experimental research (using the questionnaire method) were centralized and processed.

Table 2. Profit evolution in the 22 companies that used remote work, [million lei]

	1	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**	**13**	**14**	**15**	**16**	**17**	**18**	**19**	**20**	**21**	**22**
2019	0.4	0.3	0.2	0.1	0.4	0.1	0.5	2.2	0.4	1.1	0.5	0.3	0.8	0.1	0.3	0	0.1	0.4	0.2	0	0.3	0.2
2021	0.2	0.4	0.3	0.2	0.2	0.2	0.2	0.7	2.2	0.5	1.3	0.5	0.2	0.7	0.1	0.2	0	0.3	0.4	2.8	0	0.2
2023	0.3	0.5	0.4	0.3	0.3	0.3	0.3	0.8	2.4	0.5	1.7	0.6	0.3	0.8	0.2	0.3	0.2	0.4	0.5	0.5	0.1	0.3

First, the data on the evolution of the profit value because of the expansion of RW in the 22 companies studied were centralized. In table 2, the profit (expressed in million lei) recorded by each company in the three years subject to the study: 2019, 2021, 2023, thus including the period of the COVID 19 pandemic (2020-2022). As can be seen in the graphic representation in figure 3, many companies applying for EW recorded increases, significant.

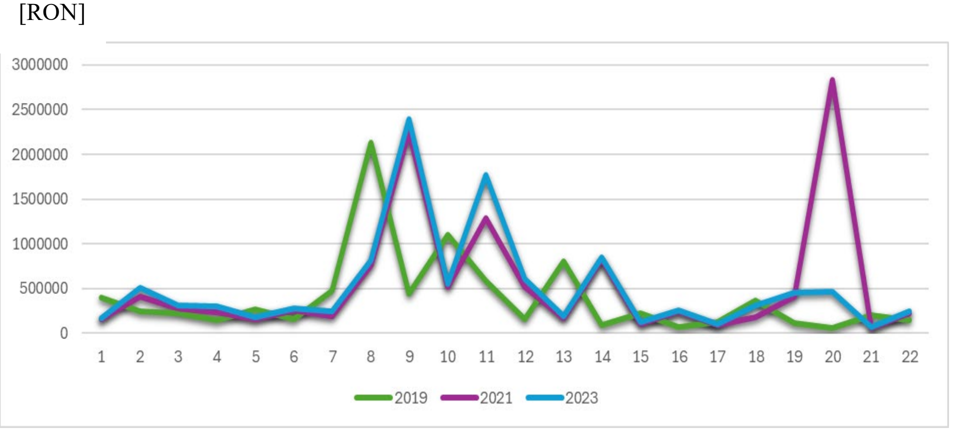


Figure 3. Profit evolution in the 22 companies that used remote work

It is noted that, in general, each company recorded a relative increase in profit, especially in the post-pandemic year 2023. The exceptions are more related to the production profile of the company.

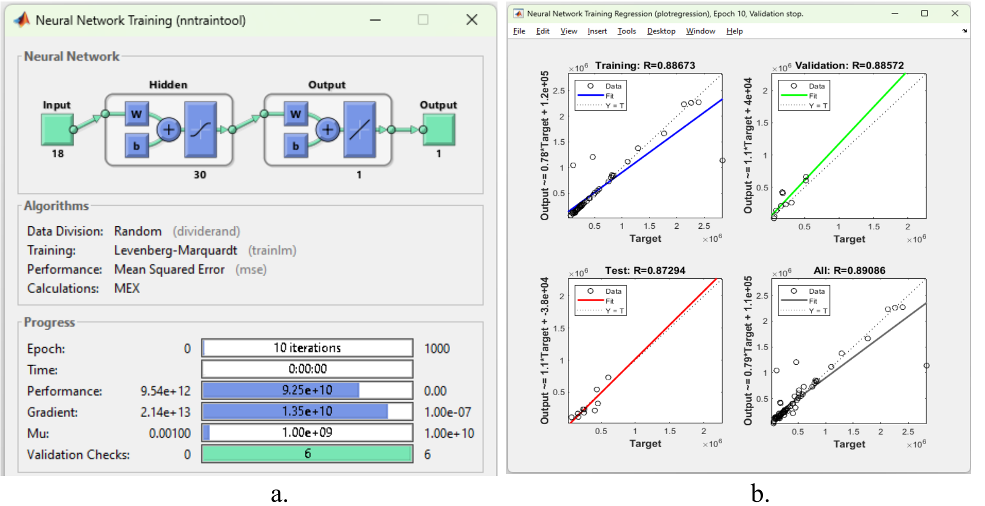
In the conditions of a rather high heterogeneity resulting from the database, this network lends itself to the study of profit predictability as an output variable, since the implied accuracy of the application was placed above 75%, therefore it was relevant. Thus, a vector with 1 component was decided as the output variable from the network.

It will calculate various statistics, including correlations, covariances and partial correlations. The R^2 level was determined, aiming at the possibility of achieving correlations in relation to the advantages and disadvantages appreciated by employers. Thus, a good correlation was obtained for variable X7, representing the intentions to expand activities, for which R^2=88.28%.

After the 30 most important factors of influence on teleworking activity were individually identified, the research advanced with data processing, considering *teleworkability* as the central indicator, and the factors of influence are reflected by variables of the defined teleworking system. Statistical methods for analyzing interdependencies between variables helped to identify several significant correlations. The Statgraphics Centurion statistical analysis method was applied to several correlations between specifically grouped variables.

In order to achieve the most objective analysis possible on the data collected through the experimental research initiated, the statistical processing of the data, the correlation analysis of the representative variable X7, which reflects the intention to expand telework, the multiple regression method on the selected variable X7 (with express meanings of the existing intentions to expand telework activities), all converged on the conclusion of the methodological advantages of the research, constituting real ways of predicting the economic and ergonomic efficiency in relation to the level of teleworkability of a commercial company.

Having available the data collected from the experimental research, the *Neural Network Training* program was run, and the architecture and training of the network are shown in figure 4. In the image on the right side of the figure, it is observed the determined values of the coefficients of determination and the accuracy of the network is 95.521% for the training stage, 95% for the validation stage and 95% for the testing stage, so a total accuracy of 95.722%.



a. b.

Figure 4. Screenshots generated by the application of the Neural Network Training program: **a.**- network architecture and training; **b.** – characterization of the accuracy of the network.

This neural network was created to predict employee behavior and perceptions under RW conditions, correlated with the profitability of the company employing. The network was built with data collected from the 634 teleworkers. The data were randomly divided as follows: 444 (70%) – the training set, 95 (15%) – the validation set, 95 (15%) – the test set. There are 18 input vectors, corresponding to the variables presented above. The output vector is profit. This newly created *Neural Networking* represents a working tool for companies that want to introduce remote work or expand the one already initiated. The network, resulting from experimental research carried out in the 22 companies, presents a high degree of generalization for other companies with agricultural activities interested in using RW in profitable conditions, ensuring good predictability of profit. It is enough to introduce the 18 input variables, to be able to predict a certain level of profit.

CONCLUSIONS

In the context where sustainable development is a priority, both in Romania and in other countries receptive to technological progress, this research tried to contribute to an improvement in the management of labor relations, in general, but with express references to the field of agriculture. Appreciating the concern for ensuring optimal labor relations, this research sought the identification, development and implementation of new solutions, as viable as possible, with a favorable impact for the future of the European Union, with a degree of uniformity in each EU component country, respecting the particularities of this one.

The optimization of labor relations, through the introduction and expansion of those carried out under the RW regime, can be ensured through responsible involvement of the applying commercial companies, but also of the qualified institutions, with a higher responsibility for managers.

Compared to the empirical use of some data processing, in this research an extra note was brought to the utility of neural networks, in combination with the tools offered by MATLAB and the Neural Fitting module, as valuable resources in the process of harmonization and regulation of RW, contributing to the improvement organizational practices and policies, promoting a positive experience for employees, as well as increasing work productivity.

Respecting the objectives of increasing labor productivity, while improving the well-being of the population, represents a necessary response, appropriate to technological and knowledge progress.

The detailed approach to the way in which RW is implemented and operates at the level of companies and institutions led to the identification of deficiencies in the management practiced at the basic level, but also at the regional and national institutional level.

In conclusion, the opportunity of this research and the importance of the results obtained are noted, confirming some expectations initially noted regarding possible solutions to improve the functioning of the entire labor relations system in the agricultural field by introducing RW, under more secure conditions, by using AI to ensure predictability of economic effects, in this case profit. Thus, both the characteristics related to achieving sustainable development objectives by correlating with the global state of the labor market, as well as the methods for optimizing the monitoring of developments, using current modern means, such as RW and AI, are highlighted.

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50. ACTUAL TASKS ON AGRICULTURAL ENGINEERING

Expert paper

ENHANCING FROST PROTECTION IN AGRICULTURE: PRACTICAL IOT AND RENEWABLE ENERGY STRATEGIES

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ABSTRACT

Recent extreme climate events in Europe have underscored the urgent need to develop effective climate change mitigation strategies in agriculture. This study investigates the potential of digital technologies, IoT sensors, and sustainable energy solutions to reduce frost damage in crops. Various frost protection methods, including infrared (IR) lights, heating wires, and wind towers that utilize warmer air from upper atmospheric levels, were tested for their effectiveness in creating favourable microclimates. Additionally, small-scale energy harvesting systems, such as Darwin wind turbines, were developed and evaluated for their ability to power these protective measures.

Data collected through remote and ground-based sensors enabled real-time monitoring of soil temperature, humidity, and frost conditions. The results suggest that these technologies may help mitigate frost damage during critical periods, such as early spring and late autumn, though further testing is needed to assess their long-term effectiveness and scalability. By integrating climate modelling with innovative mitigation strategies and renewable energy solutions, this research provides insights that could contribute to improving agricultural resilience to climate change and inform future adaptation efforts.

Keywords: *Climate change, Monitoring Solutions, IoT, Frost Prevention, Energy harvesting, Agricultural Resilience, Agriculture*

INTRODUCTION

Agriculture is profoundly impacted by climate change. Through various mechanisms, climate change brings warmer weather and changes in precipitation patterns, thus influencing crop and livestock production systems. Climate change is expected to heighten volatility in food markets, affecting both production and supply. Research suggests that climate change has a significant impact on the food system, influencing both long-term price trends and short-term price variability. Mitigation strategies such as climate-smart food systems should be adapted to ensure the mitigation of climate change on food security (Wheeler & Von Braun, 2013a).

The FAOSTAT Emission Database provides key insight into one of the mechanisms causing climate change. Agriculture is a significant contributor to greenhouse gas (GHG) emissions, accounting for nearly 30% of total anthropogenic emissions, primarily through livestock production, manure management, synthetic fertilizers, and rice cultivation. Livestock, especially through enteric fermentation and manure, produces large amounts of methane, while nitrogen-based fertilizers release nitrous oxide, a potent GHG. These emissions are amplified by deforestation and land-use changes, often associated with expanding agricultural areas. At the same time, these emissions heighten the vulnerability of the food system itself, creating a feedback loop where climate impacts and agricultural emissions are deeply interconnected. To address climate change effectively, it is crucial to enhance emission tracking within agriculture and develop strategies that reduce emissions while maintaining food security (Tubiello et al., 2013).

Farmers have independently adapted to climate change since the dawn of agriculture. However, the twenty-first century's climate challenges require deliberate and transformative strategies. Historically, farmers have adjusted their practices, such as changing planting schedules and selecting resilient crops, to maintain productivity. Yet, the current pace of climate change demands more than incremental adjustments. Planned mitigation strategies, like adopting precision agriculture and climate-resilient crops, are essential. Comprehensive policies and support systems are also needed to help farmers implement sustainable practices (Anwar et al., 2012).

Current climate change mitigation strategies include a variety of approaches that target emission reductions, energy transitions, and carbon sequestration. In agriculture, practices like enhanced soil management, crop rotations, and agroforestry aim to boost soil carbon storage while reducing greenhouse gas emissions. The use of cover crops and rangeland restoration also supports carbon sequestration but must be balanced with food production needs. However, these practices can face challenges, including high implementation costs, technical barriers, and scalability issues, particularly in resource-limited regions (U.S. Department of Agriculture, 2024). Similarly, while energy efficiency and the adoption of renewable energy sources reduce the sector's carbon footprint, their widespread application can be hindered by infrastructure demands and high initial investments. Additionally, policies promoting climate-smart agriculture—such as afforestation, improved manure management, and solar energy adoption—are crucial for meeting temperature goals and supporting sustainable development but require substantial policy support and funding to become viable at scale. These challenges highlight the need for ongoing research to refine these strategies and ensure their feasibility and accessibility across diverse agricultural contexts (Grigorieva et al., 2023).

As climate change intensifies, frost events pose significant risks to agriculture, particularly in temperate regions where late spring frosts damage flowering plants and reduce yields. Frost protection strategies include both passive and active methods, varying in effectiveness based on environmental conditions and crop types. Passive strategies focus on long-term resilience.

Site selection and ground management help reduce cold air pooling, while mulching with organic materials preserves soil warmth (FAO, 2005; Pequea, 2023). Selecting frost-resistant cultivars and adjusting planting schedules further minimize risk (Rodrigo, 2000). Active protection methods are applied during frost events. Air disturbance technologies, such as wind machines and helicopters, mix warmer inversion air with colder ground air, preventing frost damage (Ribeiro et al., 2006; Miller et al., 1971). The Selective Inverted Sink (SIS) removes cold air but remains debated in effectiveness (Battany, 2012).

Irrigation-based protection relies on the heat released during water freezing. Overhead sprinklers create a protective ice layer, while under-canopy irrigation retains soil heat (Snyder & De Melo-Abreu, 2005). Direct heating methods, such as orchard heaters, smudge pots, and biomass burning, provide localized heat but are costly and environmentally taxing (Evans & Alshami, 2009). Infrared (IR) heating and electrical heating wires have also been tested to create protective microclimates (t). Biochemical foliar applications are emerging as a frost protection approach, enhancing plant resistance to freezing, though effectiveness varies by crop and environment (Drepper et al., 2022).

The growing global demand for food, coupled with the rising costs and environmental impact of fossil fuels, underscores the urgent need to explore alternative energy sources for agriculture. Renewable energy technologies, such as solar and wind power, offer sustainable and efficient solutions, particularly for energy-intensive agricultural operations like greenhouse cultivation. These systems not only reduce reliance on conventional energy but also mitigate greenhouse gas emissions, ensuring environmental sustainability. Research into innovative energy solutions, including hybrid systems that integrate multiple renewable sources, is critical to addressing the challenges of modern agriculture while promoting resilience and sustainability in the face of climate change and resource scarcity (De Jesus Acosta-Silva et al., 2019).

Adopting renewable energy technologies like solar and wind has emerged as a transformative approach to meeting agriculture's energy needs. These systems provide clean and cost-effective alternatives to traditional energy sources, enhancing the efficiency of agricultural operations while addressing environmental concerns. Studies highlight their role in reducing carbon footprints and supporting energy reliability in the sector. By transitioning to renewable energy, agricultural practices can become more resilient to fluctuating energy costs and environmental pressures, paving the way for sustainable growth in food production (Mohammed, 2024).

The integration of innovative technologies, such as IoT sensors and energy-efficient solutions, into agricultural systems represents a transformative shift toward climate-smart practices. These advancements enable real-time monitoring of environmental conditions, precision resource management, and controlled microclimates to optimize production. However, the successful implementation of such technologies requires robust policy frameworks, financial incentives, and capacity-building efforts to ensure accessibility for farmers worldwide. By aligning technological innovation with sustainable practices and targeted policies, the agricultural sector can enhance its resilience to climate change while contributing to global efforts in reducing greenhouse gas emissions and ensuring food security (Wolfert et al., 2017).

To further investigate frost protection strategies, this study focuses on evaluating the effectiveness of technological solutions for mitigating frost damage in agriculture.

Specifically, it examines the role of digital technologies, IoT sensors, and energy harvesting solutions in creating favourable microclimates for crop protection. The study tests the application of infrared (IR) lights, heating wires, and wind towers as active frost mitigation methods, assessing their ability to prevent temperature drops and minimize frost-related damage. By analysing the practicality, efficiency, and scalability of these technologies, this research aims to contribute to the development of sustainable and adaptive frost protection strategies suitable for modern agricultural practices.

MATERIALS AND METHODS

Sensors

To measure the effectiveness of electric-based heating systems for frost protection in agricultural environments, we employed specialized sensors to capture precise temperature and humidity data. The following sensors were integrated to the study.

Figure 1. Milesight UG65

Figure 2. Milesight WS52

Figure 3. Milesight EM300

- *Milesight EM300 LoRaWAN Temperature and Humidity Sensor:* This high-precision sensor monitored real-time temperature and humidity, allowing detailed analysis of environmental conditions across both the reference (unheated) and heated areas. The sensor is depicted on Figure 1.
- *Milesight WS52x Smart LoRaWAN Electrical Socket:* This smart socket tracked energy consumption of the heating systems and provided remote activation capabilities, supporting efficient control and precise monitoring of power usage. Smart electrical socket is depicted on Figure 2.

Sensor Deployment and Connectivity

The sensors were integrated into the TELOS remote monitoring system, which transmitted data through *Milesight LoRaWAN Base Stations*, presented on Fig. 3, enabling connectivity via LAN with a range of up to 7 km. The system's configuration allowed sensors to be placed at multiple distances and heights to capture temperature variations accurately, supporting a nuanced assessment of the heating system's impact.

For research purposes we built and tested a sensor utilizing a Mobotix thermal camera shown on Figure 4 that was used to gather additional pictures shown in results.

Figure 4. CAD drawing

Figure 5. MOBOTIX thermal camera with dedicated electronics

Frost prevention

We tested three different models of active frost prevention during our testing. The first concept utilized a heating cable commonly used for frost prevention in water draining systems. The second concept utilized IR lamps which are commonly used in animal husbandry. The third concept utilizes a ventilation system that rely on mixing air layers and preventing frost.

Heating Cable

We performed two experiments with heating cables. In the first experiment the heating cable was placed in a vineyard and in the second experiment the heating cable was placed in an apple orchard. Both experiments took place at Estate Zobec located in the Steyer region in Slovenia. Coordinates of the experiment were : 46.35752017230773, 15.632438535227502. The experiments were conducted on 22.4.2024.

We utilized the technique of 3D printing to make simple fixtures shown in *Figure 6* that would bind the heating cable and the plant together as shown in Figure 7. Exactly the same principle was used in the orchard.

The first system utilized a heating wire placed approximately 60 cm from the ground, which was locally adjusted to the height of the buds we wish to protect from frost. With the technical characteristic of only drawing 20 W per meter it presented itself as a relatively efficient but rudimentary way of frost protection.

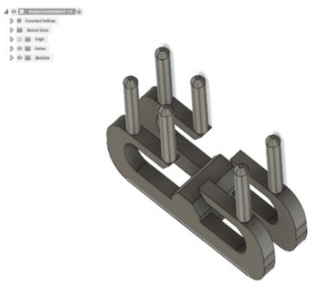


Figure 6. CAD drawing of clamp

Figure 7. Installation in vineyard

The second iteration of the same system presented in *Figure 8* implemented a slightly newer version of the heating cable that draws 25 W per meter. The newer system also featured a controller to enable the user of easily and instantly turning the system on and off during extreme climactic events.

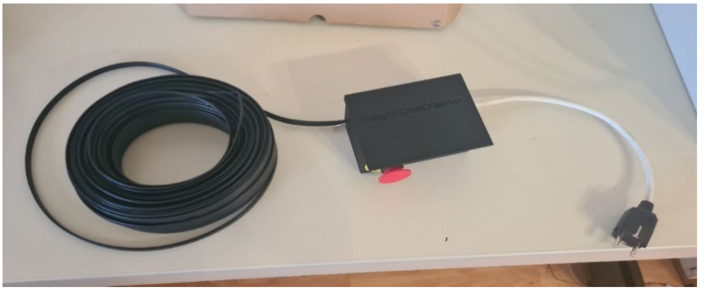


Figure 8. Heating cable system with controller

IR Lamps

For the second model we used commercially available infra-red bulbs (*Figure 9*). For which we designed and printed custom 3D brackets that enabled wiring in series (Figure 10). Thus, making the design simple, effective and economical. For this experiment we wired 10 light bulbs which when measured were drawing a little under 2 kW of power. The bulbs were placed 2.5 meters apart at the height of 2.5 meters as shown in Figure 11. This experiment was carried out at Sadjarstvo Slom d.o.o located in Ponikva, Slovenia. Coordinates 46.24065857666187, 15.434777266462145.

Figure 9. Philips 175W bulb

Figure 10. 3D printed socket

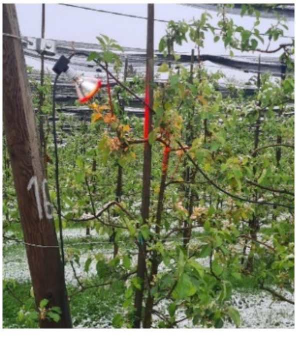


Figure 11. Installation in orchard

Mobile wind turbine

The third concept of frost prevention aimed at preventing frost damage in an asparagus field with the usage of a ventilator. The whole assembly was attached to a tractor for easier transportation and manipulation. The system allows injecting warmer air from above to ground level and in theory creating a favourable microclimate. The system used on average 6.58 kW of electrical energy. The system is presented in Figure 12.

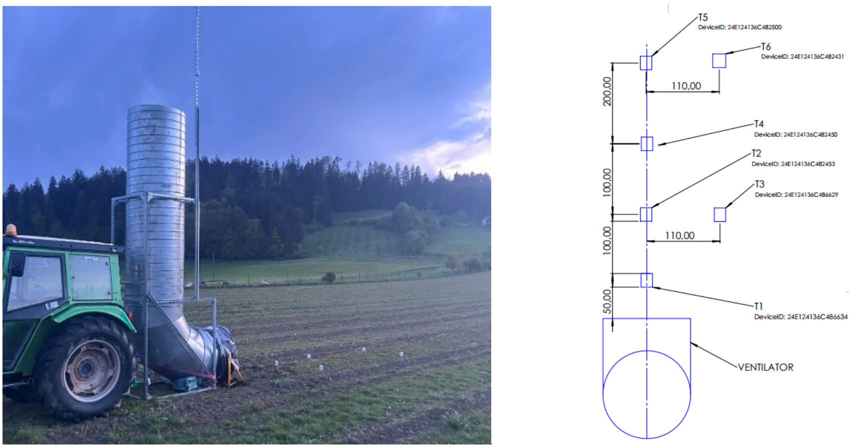
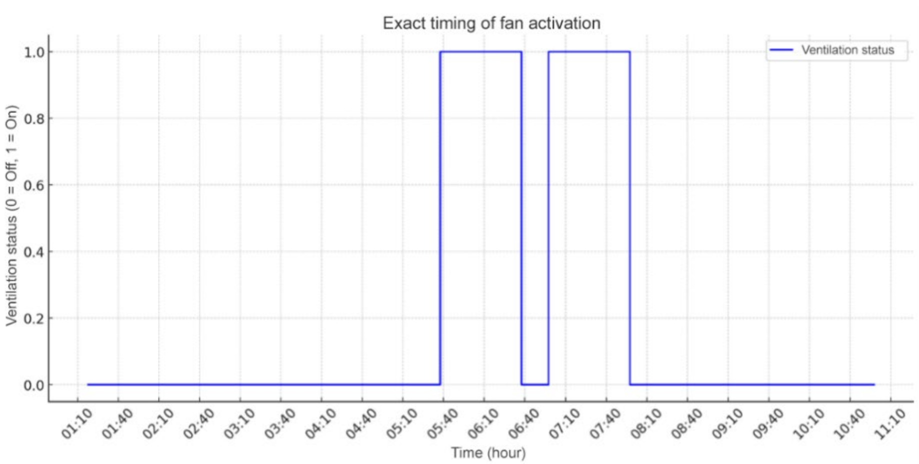


Figure 12. Mobile wind turbine and sensor placement.

Data was gathered by 7 Milesight sensors. The first sensors titled “Temperatura_20C” was our reference control sensor and other 6 sensors were placed in the path of the ventilator. To accurately measure the results the experiment required a punctual start of the ventilator and sensor system. The system was turned on at exactly 5.40 for the duration of one hour before it was shut off. After 20 minutes the system was started again for the duration of one hour (Graph 1), and shows a strong correlation between sensors and control.



Graph 1. Exact timing of fan activation

Renewable energy solutions

In terms of sustainability in agriculture we wanted to investigate means of harvesting and storing energy. Taking this into account, we set and devised multiple small-scaled energy harvesting systems that were used to power IoT devices. These could be eventually scaled up to power other equipment, possibly even devices used in frost prevention scenarios. (De Jesus Acosta-Silva et al., 2019)

The Hybrid Darwin Wind Turbine (HDWT) system is primarily designed to harness wind power and convert it to electrical energy. But in our case, it was upgraded to include also photovoltaics to harvest solar energy to provide a renewable, portable power source for agricultural workers / tasks. The system's core components include small solar panels, a simple wind turbine, a 3D-printed housing, and various DC/DC voltage converters to stabilize energy flow.

The materials used for the Hybrid Darwin Wind Turbine (HDWT) system included 1 kg of PLA white plastic, utilized for 3D-printing the housing; three solar panels, each rated at 6 V and 1 W, for harvesting solar energy; and a wind turbine rated at 5 V and 3 W to convert wind energy into electricity. To ensure stable voltage output, a 5 A DC/DC step-down converter and a 2 A DC/DC step-up converter were incorporated. Additionally, a 20 Ah rechargeable battery was included to store the generated energy and provide consistent power output.

The setup was installed and tested at an apple orchard at Slom d. o. o.. The system was mounted on-site and tested under variable wind and sunlight conditions.

Figure 13. Hybrid Darwin Wind Turbine

RESULTS AND DISCUSSION

Heating Cable

Based on visual results we noticed that the heating wire was only able to heat up a small circumference around itself and providing very limited crop protection, which was inadequate for the apple orchard. Our testing of the heating wire in the vineyard proved semi-promising.

Figure 14: Thermal image of the heating wire captured by MOBOTIX depicts a thermogram taken by our thermal camera and shows the heating element evenly radiating heat. To further explore the potential of this crop protection method, additional experiments are warranted, given its low energy consumption and straightforward design, which make it a promising solution.

Figure 14. Thermal image of the heating wire captured by MOBOTIX combined with an RGB image

Ir Lamps

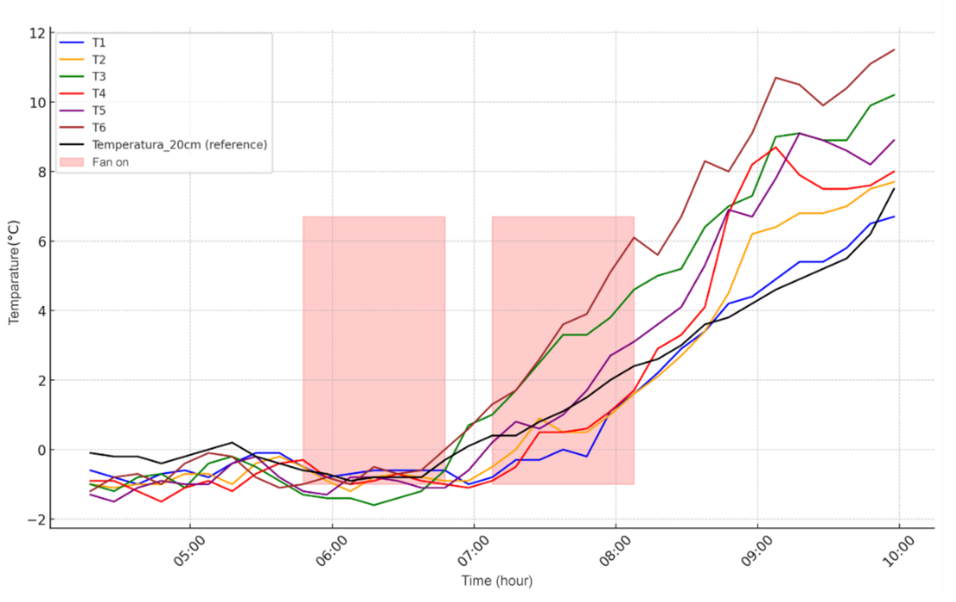
The IR based heating bulb system proved more promising. As shown in *Figure 15* the heating bulbs provided enough heat to melt the snow and offer significant protection especially when compared to our control (shown on right).

Figure 15. Test orchard during snowstorm

Mobile wind turbine

Our experiments with the ventilator system showed that injecting air from heights did not significantly impact ground-level temperatures. The fan system did not cause significant changes in temperature either relatively or absolutely. Confirming the statement of Tadić, et al. 2023 that the performance of wind machines is low. Sensor temperatures remained largely unaffected before and after the fan was turned on.

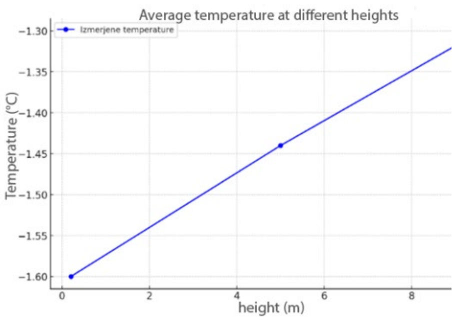
Looking at the data, there was a high correlation with ground temperature. All temperature sensors showed a strong correlation with the reference ground temperature, indicating consistent thermal patterns across the field unaffected by the fan. Minimal changes in extreme temperatures were observed, with only slight variations in the minimum and maximum temperatures recorded after the fan was activated, further suggesting limited influence on frost prevention. This is demonstrated in Graph 2.



Graph 1. Comparison of temperatures from 4:00 a.m. to 10:00 a.m

Further thought experiments investigated the effectiveness of capturing warm air from higher altitudes to improve frost prevention. Measurements at different heights: 0.2 m, 5 m and 10 m, revealed a consistent temperature gradient of approximately 0.3 °C across 10 meters. The results, shown in Figure 16 and Figure 16, suggest that while warm air is present at higher altitudes, the current height of 5 m is insufficient for effective warm air capture.

A linear regression model (Figure 17) demonstrates that increasing the system height to at least 10 m is required to achieve meaningful temperature improvements near ground level. This finding highlights the need to redesign ventilation systems to take advantage of the temperature gradient. To enhance the performance of ventilation systems for frost prevention we would recommend increasing the system height from 10 to 20 meters to better utilize the observed temperature gradient.



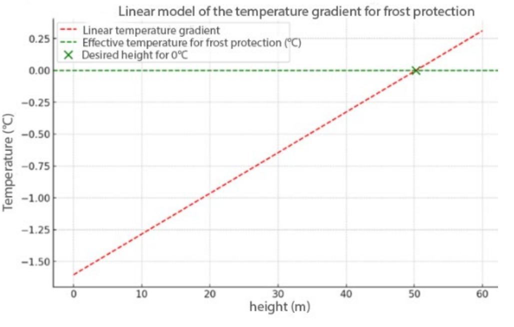
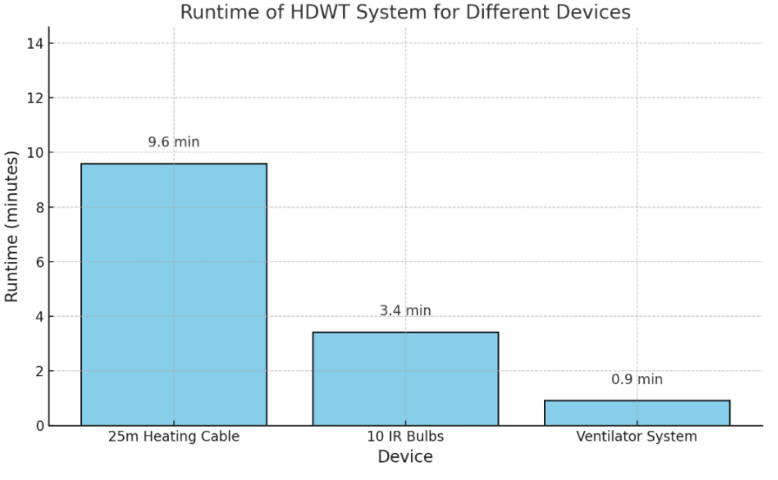


Figure 16. Measured temperatures

Figure 17. Linear regression model of the temperature gradient

Renewable energy solutions

Graph 3 illustrates that our small-scale, theoretical model of the HDWT system shows promise for low-power, short-duration applications in agriculture. While these findings are preliminary, they suggest that, with further refinement, the system could evolve into a sustainable and cost-effective solution for targeted use. Similar findings of Mohammed, 2024 provide us with insight that further research would be beneficial.



Graph 2. Runtimes of different active measures presented in a chart

CONCLUSIONS

Our field tests of the heating cable system were not as successful as we had initially expected. However, since the low cost and ease of use, we would like to continue our research in this area, by focusing on its impacts on root systems.

We concluded that using of IR light bulbs commonly used in animal husbandry proved successful in plant protection. They are easy to install, trigger and provide a way to target the necessary area and prevent frost. They downside is their high-power consumption and energy that is not transferred into heat on the plants, but in the surrounding area.

The ventilator system experiment concluded that the fan system did not significantly impact ground or near-ground microclimatic conditions in this setting, as confirmed by the negligible temperature differences before and after fan operation. High correlations between sensor readings and limited shifts in extreme temperatures support this finding. A linear regression analysis of temperature gradients at various heights indicated that the current fan height of 5 meters is insufficient for effective warm air capture, suggesting that increasing the system height could enhance its efficacy in frost prevention.

Future research could explore the potential of capturing and reusing the dissipated heat from infrared light bulbs used for plant heating. By integrating this heat recovery with a ventilation system, the otherwise lost thermal energy could be redirected to enhance the overall efficiency of frost prevention. This approach could not only minimize energy waste but also contribute to creating a more sustainable and cost-effective solution for agricultural applications.

The HDWT system offers a promising, portable, and low-cost energy solution for targeted frost protection. While its current energy storage limits its use for large-scale methods, future advancements—such as higher-capacity batteries, modular designs, or more efficient technologies—could enhance its applicability. These developments would align the system's renewable energy capabilities with the growing demand for sustainable and adaptive agricultural practices.

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50. ACTUAL TASKS ON AGRICULTURAL ENGINEERING

Expert paper

CONTRIBUTIONS TO THE PERFORMANCE OF FIRE EXTINGUISHING SPRINKLER SYSTEMS

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ABSTRACT

In agro-industrial environments and greenhouses, the implementation of sprinkler fire suppression systems presents significant challenges due to the complexity of these settings, which include large-scale material storage, diverse structures, and dynamic operational conditions (Zhang et al., 2024). Key technical challenges involve spray cone height limitations, optimal sprinkler head placement amidst obstacles, airflow disturbances, and variable heat intensity. Effective fire suppression depends on addressing these issues through precise design and execution. A critical factor in system performance is the size and velocity of water droplets, which influence the kinetic energy transferred to the target surface. This study employed a Laser Precipitation Monitor (LPM) to measure droplet size and velocity from 10 mobile sprinkler heads, providing accurate real-time data on spray dynamics (Zhang et al., 2024). Such measurements are essential for evaluating sprinkler efficiency and ensuring an optimal droplet size distribution for effective fire suppression (Lougheed, 1989). Additionally, imaging systems were utilized to assess sprinkler performance, offering precise data on droplet distribution to ensure consistent coverage during fire operations (Galea, 2000). This article provides solutions and recommendations structured around design, installation, and operational phases. By integrating advanced measurement techniques and addressing challenges related to droplet dynamics, airflow, and heat variability, sprinkler systems in agro-industrial and greenhouse settings can be optimized for reliability and efficiency in fire suppression (Kincaid, 1979).

Keywords: *Agricultural engineering, Fire suppression, Uniformity coefficient (CUC), Laser Precipitation Monitor (LPM).*

INTRODUCTION

In agro-industrial environments and greenhouses, the use of fire suppression systems, particularly sprinklers, plays a crucial role in safeguarding large-scale facilities and stored materials from fire hazards (Grimwood, 2003). However, the design and implementation of these systems present unique technical challenges that require careful consideration to ensure their effectiveness. These challenges are influenced by the complex structures of agro-industrial greenhouses, the extensive storage of various materials, and dynamic operational environments, which include factors such as airflow and varying heat intensities. Recent research has highlighted the role of advanced fire suppression technologies in ensuring uniform water distribution in agro-industrial settings (Ortiz-Rodríguez et al., 2022; Boyko et al., 2024). Automated irrigation systems have also been shown to enhance efficiency in greenhouse environments, particularly in large-scale water distribution (Darwish & Eldeeb, 2024).

Key obstacles in designing efficient sprinkler systems for these environments include limitations in sprinkler spray cone height, proper placement of sprinkler heads amidst potential obstructions, and the impact of air currents on the distribution of water droplets (Kincaid, 1979). Additionally, the varying intensity of heat generated by stored materials over time further complicates the ability of sprinklers to effectively suppress fires. Addressing these challenges is critical to ensuring that sprinkler systems can provide reliable and comprehensive fire protection.

This study explores solutions to these issues by focusing on the design, installation, and operational phases of sprinkler systems in agro-industrial environments and greenhouses. A significant aspect of improving sprinkler performance lies in optimizing droplet size distribution and velocity (Chigier, 1991), which directly impact the kinetic energy transferred to the target surface during fire suppression. Utilizing advanced measurement techniques, such as the Laser Precipitation Monitor (LPM), provides real-time data on droplet behavior, offering valuable insights into how water application rates and droplet dynamics affect overall system performance (Zhang et al., 2024).

Recent research has shown that uniform water distribution plays a crucial role in fire suppression effectiveness, particularly in controlling heat diffusion (Fernando et al., 2015; Martins et al., 2023). Computational models further indicate that high-precision droplet monitoring improves sprinkler efficiency in greenhouse fire suppression systems (Koul et al., 2022). Through the application of precise measurement tools and a deep understanding of the factors influencing sprinkler efficiency, this research aims to enhance the reliability and effectiveness of fire suppression systems in agro-industrial environments and greenhouses.

MATERIALS AND METHODS

Description of the Mobile Experimental Stand for Sprinklers

To simulate the fire suppression systems used in the built agro-industrial environment, we used a mobile experimental stand for sprinklers. The general dimensions of the sprinkler stand are as follows: Stand Height: 2000 mm Stand Width: 2000 mm; Stand Length: 3000 mm; Base Height: 1000 mm and Total Stand Height: 3000 mm. These dimensions are essential for understanding the spatial requirements and positioning of the sprinkler system within a facility. The base height of 1 meter provides an elevated platform, allowing for optimal distribution of water, while the total height of 3000 mm aligns with the standard measurements used by manufacturers to evaluate the performance of the sprinkler spray cone. This ensures that the system adheres to industry standards for effective fire suppression coverage.

The stand is constructed using 2-inch zinc-coated (Zn) pipes, forming a durable and robust framework. These pipes are arranged both vertically and horizontally to create a sturdy support structure that is ideal for mounting sprinklers.

Key features of the stand include:

- *Mobile structure*: The stand is equipped with *four wheels*, allowing for easy maneuverability, and repositioning as needed.
- *Threaded plug connections*: The stand is fitted with *1/2-inch and 3/4-inch threaded plug fittings*, arranged alternately to allow for flexible installation of various sprinkler types.
- *1/2-inch threaded plug fittings*: 8 pieces.
- *3/4-inch threaded plug fittings*: 8 pieces.
- *Pump connection*: The stand also includes a *2-inch connection* designed for connecting pumps with flow rate parameters *Q = [specify mc/h] and H = [specify mH2O]*, ensuring compatibility with firefighting systems.

Sprinklers are installed on these threaded connections, evenly distributed across the stand to ensure maximum coverage.

A typical sprinkler example is shown in Figure 1. Water discharged from the sprinkler's circular orifice forms a water jet. This jet strikes the metallic deflector, which redirects the flow and transforms it into a spray pattern. The deflector is rigidly positioned by two metal arms on either side of the sprinkler. Water leaves the deflector in thin streams, called ligaments, which break into droplets due to surface tension. The water flow rate for a sprinkler typically ranges from 1.8 to 7.6 liters per second, producing approximately 108 droplets in the air for each sprinkler (Huang, 1970).

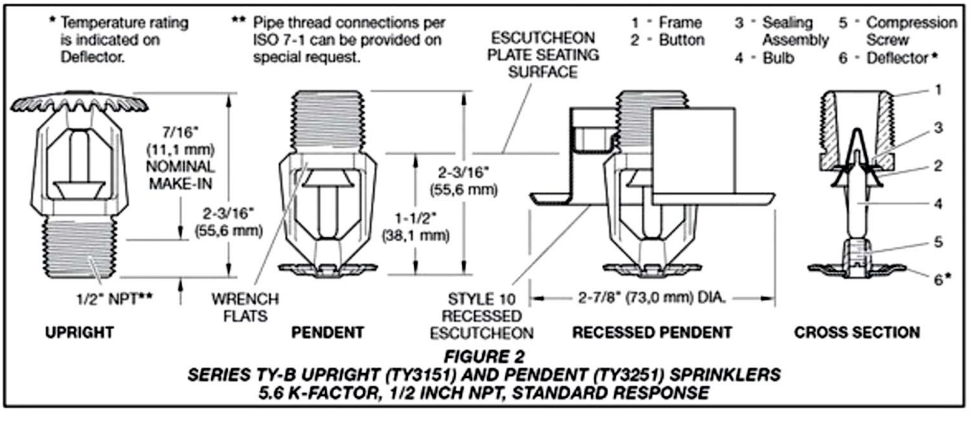

Figure 1. Geometric characteristics of fire suppression sprinklers and installation methods

Two types of *bronze low-head sprinklers* are mounted on the top bar of the stand, ensuring a balanced distribution pattern:

- Bronze Low Head Sprinkler 1/2" – operating at 68°C, with a K80 flow factor, standard model.
- Bronze Low Head Sprinkler 3/4" – operating at 68°C, with a K115 flow factor, standard model.

Each threaded plug connection is assigned one of these two types of sprinklers to maintain an alternating, evenly distributed configuration:

- 1/2-inch threaded plug fitting -> Bronze Low Head Sprinkler 1/2".
- 3/4-inch threaded plug fitting -> Bronze Low Head Sprinkler 3/4".

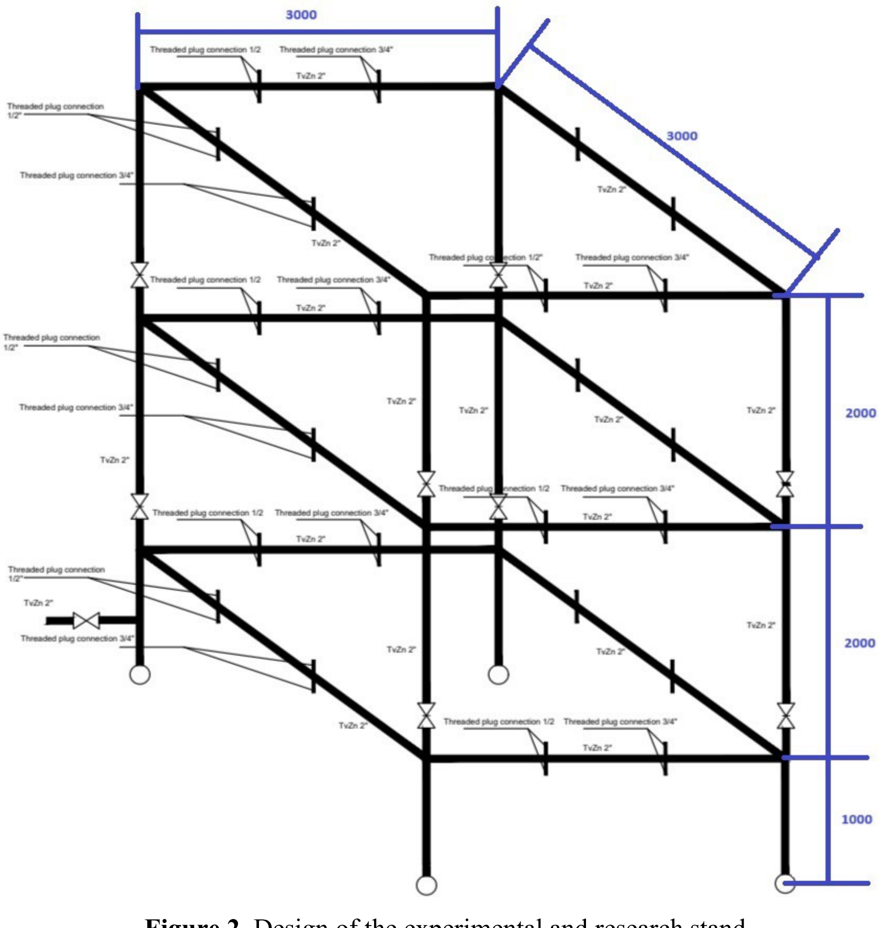

Figure 2. Design of the experimental and research stand

This configuration ensures that the sprinklers provide a *uniform and effective distribution of water*, enhancing the system's fire suppression capabilities (Galea, 2000). The specific arrangement of the sprinklers allows for optimal coverage of the target area, improving fire protection performance. The stand is segmented into multiple sections, each measuring 1000 mm in width and 3000 mm in length, forming a well-organized framework that serves as a support network for the mounted sprinklers. This modular design ensures that the stand is structured into distinct areas, allowing for *efficient distribution, and mounting of the sprinklers* across the entire surface. The division into sections also enhances the overall stability and flexibility of the system, making it easier to adjust or reconfigure the sprinkler arrangement based on specific requirements. By organizing the stand into these well-defined sections, the sprinkler system achieves both *maximum efficiency in fire suppression* and *ease of maintenance*, as individual sections can be accessed or modified without affecting the entire structure.

The stand is designed to accommodate the simultaneous mounting and testing of multiple sprinkler heads, providing an ideal setup for evaluating water distribution patterns and the overall performance of sprinklers in controlled experimental conditions. Key data points such as flow rate, operating pressure, and spray uniformity can be measured, offering valuable insights into how efficiently each sprinkler distributes water across a designated surface area (Bukowski, 1996). Equipped with alternating 1/2 inch and 3/4-inch threaded connections, the stand allows for easy swapping and reconfiguration of different sprinkler models. This flexible setup supports the testing of a variety of sprinkler types, making it adaptable for a wide range of experimental scenarios or performance evaluations.

For more accurate data collection, containers such as trays or precipitation cylinders can be placed beneath each sprinkler head to measure the exact volume of water distributed and assess the evenness of coverage across the surface. This method helps in determining the efficiency of the water application and ensures that sprinklers meet performance standards.

Type of Sprinkler and General Characteristics:

- Sprinkler 1, Bronze Pendent 1/2"; 68°C, K 80, Standard
  - Model: Pendent sprinkler, bronze.
  - Connection Diameter: 1/2 inch.
  - Operating Temperature: 68°C.
  - K-Factor: 80 (metric units).
- Sprinkler 2, Bronze Pendent 3/4"; 68°C, K115, Standard
  - Model: Pendent sprinkler, bronze.

Flow Characteristics:

- Sprinkler 1:
  - K-Factor: 80.
  - Flow Rate Formula: $Q = KPQ = K\sqrt{P}$
  - Where:
    - Q is the water flow rate (l/min),
    - K is the sprinkler coefficient (l/min·bar^0.5),
    - P is the pressure at the sprinkler head (bar).
  - Calculation Example:
    - At 1 bar: $Q = 80\sqrt{1} = 80$ l/min.
    - At 2 bar: $Q = 113\sqrt{2} = 113$ l/min.

- Sprinkler 2:
  - K-Factor: 115.
  - Flow Rate Formula: Q = KPQ = K√P
  - Where:
    - Q is the water flow rate (l/min),
    - K is the sprinkler coefficient (l/min·bar^0.5),
    - P is the pressure at the sprinkler head (bar).

Operating Pressure:

- Pressure is typically between 1 and 2 bar.

Spray Height:

- Installation Height (H) depends on installation specifications and ceiling mounting height.

Minimum Cross-Section of the Spray Cone:

- Approximately 2–3 meters (standard height).

Maximum Cross-Section of the Spray Cone:

- Up to 4–5 meters (depending on operating pressure and system configuration).

The stand can be equipped with additional instruments such as distrometers or other measurement tools to capture data on the size, velocity, and quantity of water droplets within the sprinkler's spray cone (Prahl, 1988). This advanced monitoring allows for a more detailed analysis of the sprinkler's performance, ensuring that the water distribution is both effective and precise for fire suppression or other operational requirements. This experimental stand, with its flexible configuration, precise measurement capabilities, and capacity for real-time monitoring, provides a comprehensive platform for testing and optimizing sprinkler systems (Wendt, 1986), ensuring that they perform efficiently under various conditions (Kincaid, 1979).

These specifications often include performance charts, spray distribution diagrams, and installation instructions, which can provide precise information about flow rate, pressure, and spray cone dimensions.

Determining the Christiansen Uniformity Coefficient (CUC) to Evaluate Water Distribution Uniformity of Sprinklers:

A detailed methodology is proposed for using the Christiansen Uniformity Coefficient (CUC) to assess the uniformity of water distribution over a triggered area, specifically in the context of the experimental stand.

Water Collection:

1. Collection Trays:

- Flat trays of various sizes are used to collect and measure the water distributed by the sprinklers. These trays are typically made of waterproof materials and are positioned in the field to capture the sprayed water.

Proper Use of Collection Containers:

1. Positioning the Containers:
- The trays/containers are arranged in a dense matrix under the sprinkler spray area to capture variations in water distribution. The matrix consists of four trays, each with dimensions of LxWxH = 1500 mm x 1500 mm x 400 mm, and a volume of 0.9 m^3. The total collected water volume is 3.6 m^3 (Kincaid, 1979).

2. Measuring the Water:
- After collecting the water, the volume in each container is measured to calculate the water depth (hi).

3. Data Analysis:
- The collected data are used to calculate the average water depth, absolute deviations, and the uniformity coefficient.

For the *experimental setup* eight sprinkler heads are placed on the top of the stand, according to the design. The sprinklers are positioned at specified distances on the stand and are mounted in a pendent or upright orientation using 1/2-inch and 3/4-inch threaded fittings on the top bar. All other openings in the structure are sealed with plugs. The stand is connected to a pump system to ensure minimum and maximum flow parameters (Q) and pumping head (H), as well as to a water supply capable of providing the necessary volume for at least 30 minutes at maximum flow and to a water source capable of providing the required volume for at least 30 minutes at maximum flow rate and pressure, accounting for linear, local, and geodetic head losses, as well as the operating pressure. A flowmeter can also be installed between the pump and the stand connection. A pressure gauge is mounted on one of the top bars using a 1/2-inch fitting (Kincaid, 1979).

RESULTS

The measurement area under the experimental stand is established, considering that it needs to be protected, covering the entire spray area of the eight (or four) sprinklers. Collection containers (e.g., collection boxes) are arranged in a dense matrix within this area, with a total surface area equal to the calculated sprayed area, to capture droplets and variations in spray intensity from the overlapping sprinkler spray cones. Σ\ sum Σ Base Area of Boxes + Σ \ sum Σ Sprinkler Spray Area in the Sections of the Spray Cone Corresponding to the Protected Area.

For *measuring water volume*, the pump system is activated after confirming that the water source ensures the required pumping flow. The system is filled, and air is released through an automatic air vent, or a venting vessel installed at the top of the stand. All eight (or four) sprinkler heads are operated simultaneously, and water is collected in the containers for a predetermined period (e.g., 30 minutes). The volume of water collected in each container is measured, and the water depth (hi) is calculated at each measurement point (Zhang et al., 2024).

Calculating the Average Water Depth

The average water depth (hm) is calculated using the following formula:

$$h_m = \frac{1}{n}\sum_{i=1}^{n}(hi) \quad (1)$$

where: n is the number of collection containers,
hi is the water depth measured in each container.

Calculating Absolute Deviations
The absolute deviations from the average water depth are calculated as:

$$(| \text{hm} - \text{hi} |) \quad (2)$$

for each measurement point.

Calculating the Christiansen Uniformity Coefficient (CUC)
The sum of absolute deviations is calculated as:

$$\sum_{i=1}^{n} | \text{hm} - \text{hi} | \quad (3)$$

The CUC is calculated using the formula (Christiansen, 1942):

$$\text{CUC} = [1 - (\sum_{i=1}^{n} | \text{hm} - \text{hi} |)\ \boldsymbol{x} \frac{1}{n\ x\ hm}] = \times 100\% \quad (4)$$

This formula provides a measure of the uniformity of water distribution across the area.

The calculations were carried out in tabular form based on the measurements taken from Sprinkler Head 1 at an operating pressure of P = 1 bar, recorded every 5 minutes up to 30 minutes. The results are presented in Table 1.

The absolute deviations range between 0.5 mm and 3.25 mm, which are relatively small compared to the average depth, suggesting that the water distribution in the four trays is very uniform. This uniformity is essential for fire suppression systems, as a homogeneous water distribution across the entire protected area helps reduce temperatures and prevent the spread of fire. The largest deviations occur at t6 (30 minutes), when the total water volume is at its maximum. Even under these conditions, the distribution remains uniform, indicating reliable system performance in scenarios with higher water flow rates.

Table 1. Calculating the Christiansen Uniformity Coefficient (CUC)

Measurement Time	Water Depth in Tray 1-h1 [mm]	Water Depth in Tray 2-h2 [mm]	Water Depth in Tray 3-h3 [mm]	Water Depth in Tray 4-h4 [mm]	Average Water Depth - hm [mm]	Calculation of Absolute Deviations from the Average Water Depth				Sum of Absolute Deviations	Christiansen Uniformity Coefficient (CUC) [%]
						Tray Deviation 1 [mm]	Tray Deviation 2 [mm]	Tray Deviation 3 [mm]	Tray Deviation 4 [mm]		
t_0 =0 min	0	0	0	0	0	0	0	0	0	0	100
t_1 = 5 min	44	42	45	43	43,5	0,5	1,5	1,5	0,5	4,0	97,70
t_2 = 10min	89	85	87	90	87,75	1,25	2,75	0,75	2,25	7,0	98,00
t3 = 15 min	133	131	130	135	132,25	0,75	1,25	2,25	2,75	7,0	98,68
t4 = 20 min	178	179	175	173	176,25	1,75	2,75	1,25	3,25	9,0	98,72
t5 = 25 min	222	220	223	225	222,5	0,5	2,5	0,5	2,5	6,0	99,33
t_6 =30 min	267	261	264	263	263,75	3,25	2,75	0,25	0,75	7,0	99,34

The CUC values, ranging from 97.70% to 99.34%, demonstrate a good uniformity of water distribution, which is essential for an effective fire suppression system. A high CUC suggests that water is evenly dispersed in all directions, reducing the risk of leaving certain areas uncovered. This very good uniformity indicates that at a pressure of 1 bar, the sprinkler effectively covers the protected area, ensuring that the entire surface receives an adequate amount of water to control or extinguish a fire (Lougheed, 1989).

CONCLUSIONS

The sprinkler's performance at a pressure of 1 bar is very good, ensuring a uniform water distribution across the entire protected area. This is important for the fire suppression system's efficiency, as uniform distribution contributes to effective cooling and fire extinguishment. The small deviations suggest that during the test, all four trays received comparable amounts of water, indicating that the water flow is well controlled and there are no preferential directions in which the water is dispersed. This implies good alignment of the discharge nozzle and an optimal geometric configuration of the deflector. The high CUC (above 97%) confirms that at this pressure, the fire suppression system can deliver water uniformly, effectively covering the entire protected area. This is particularly important for protecting large surfaces and minimizing the chances of fire rekindling (Lougheed, 1989).

The successful implementation of fire suppression sprinkler systems in agro-industrial environments and greenhouses requires addressing a range of unique challenges related to the physical and operational characteristics of these settings. These challenges include managing the limitations of sprinkler cone height, optimizing the placement of sprinkler heads amidst obstacles, countering airflow disturbances, and dealing with variable heat intensities (Galea, 2000).

To ensure the effectiveness of these systems, key factors such as the size and velocity of water droplets, which directly influence the kinetic energy transferred to the extinguishing surface (Puchovsky, 2002), must be carefully monitored, and controlled. Advanced tools like the Laser Precipitation Monitor (LPM) offer critical insights into droplet dynamics, enabling more precise measurements and improved system performance. Advances in smart monitoring systems have improved fire suppression efficiency by integrating IoT-based sensors for real-time data collection (Talavera et al., 2017; Afonso et al., 2023). Such systems enable precise adjustments to sprinkler operation based on environmental factors such as humidity, temperature, and airflow (Egea et al., 2018). These methods, combined with a thoughtful approach to system design, installation, and operation, provide a path to more reliable and efficient fire suppression in complex agro-industrial environments. After applying the CUC method to determine spray distribution and confirming it is uniformly distributed, droplet size measurements can be conducted in each section of the spray cone using an LPM or a distrometer (Yao, 1997).

The findings of this study align with previous research that emphasizes the importance of integrating automation, AI-based controls, and smart sensors in fire suppression systems (Butsenko et al., 2020; Egea et al., 2018). Future studies should explore how renewable energy sources can further enhance the sustainability of fire suppression irrigation in greenhouses (Talavera et al., 2017). By continuously refining these techniques and addressing the multifaceted challenges inherent to these systems, sprinkler-based fire protection can be optimized to ensure enhanced safety and performance in high-risk industrial set and in other environments.

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50. ACTUAL TASKS ON AGRICULTURAL ENGINEERING

Preliminary communication

SOLUTIONS FOR SHREDDING MANUFACTURING EQUIPMENT USING CAD AND INDUSTRY 4.0

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ABSTRACT

Traditional manufacturing involves selling physical products. Computer Aided Technologies, particularly CAD and CAM, have been used for a different business model in the agricultural field: customizing virtually designed manufacturing equipment solutions to customer order. This is a new business model as a service. The manufacturing equipment solution architecture has been virtually designed in CAD. Reverse engineering has been used to obtain the digital twin of physical manufacturing equipment and use it as input in CAD. This enables physical manufacturing equipment to be replaced by 3D drawings. The aim is to improve the performance of the manufacturing process via quantifiable key performance indicators. The methodology is an experiment on a real production plant at Cenei funded by the European Union and used for academic purposes. Results show it is possible to reverse engineering physical products and use CAD and CAM related technologies to architect manufacturing solutions generating better key performance indicators compared to selling physical products devices. The device manages cutting and shredding. The virtually designed manufacturing equipment intakes three times more raw material. Simulation and reverse engineering are key technologies in Industry 4.0. For the paper we have an evolution of the solution architecture for cutting and shredding manufacturing equipment by 3 stages that will show how evolution has a great impact on costs, time production and how efficient it could be.

Keywords: *New Technology, Green Energy, Blade Design and Optimization, Reverse Engineering, Agroindustry*

INTRODUCTION

The wood pellet market is booming in Europe. The EU 2020 policy targets renewable energy sources and greenhouse gas (GHG) emissions reduction are among the main drivers. Today's manufacturing operations integrate resources in a more complex manner and global scale. Such levels of scale and complexity require extensive collaboration.

The integration of robotic systems in agricultural environments, such as greenhouses, enhances productivity by automating labor-intensive tasks and optimizing resource utilization (Maris et al., 2017)

Mold pellet production starts with a CAD-created 3D model, integrated into a cloud manufacturing system for efficient production and monitoring. In our situation, using reverse engineering will help us to study some old parts that were used a long time ago by the entire process, and make them even better and easier to produce.

The design and development of straw bale shredders focus on enhancing operational efficiency by optimizing blade configurations and feed mechanisms, ensuring minimal clogging and uniform output (Kumar, Dogra, & Manes, 2021)

The impact of Industry 4.0 in our situation of optimization will give us a positive answer to the questions about productivity, data processing, industrial connectivity, predictive engineering, and sustainability. It will also be a step ahead in the digitalization of all resources that are in need to implement a production system. „Industry 4.0 thus represents the new wave in the technological evolution of production, stimulating more and more companies to meet the new standards set by a constantly changing market, by transforming production units into "smart factories" (Wang et al., 2016).

The process of pelletization and the key factors that are involved were described by Maris et al(2017). Since then, the production line was modified and optimized using graph theory

The implementation of Industry 4.0 technologies in the design and manufacturing of molds for pellets and briquettes demonstrates a significant improvement in production efficiency and customization capabilities (Matei et al., 2023)

MATERIALS AND METHODS

Theoretical aspects

This research focuses on the use of reverse engineering and industry 4.0, and their role in the optimization of the manufacturing and product design of shredding machines for straw.

From what is already known, production means the creation of a new concept that will revolutionize the present situation in production. This economic profitability and time management are determined by our four types of technics. The modern manufacturing industry is exposed to high competitiveness on a global scale and largely variable demands, which negatively affect manufacturing resource efficiency.

The main objective of this study is to find a more efficient way to optimize the manufacturing and product design of chopper that will be more efficient in production and on the cost of production and electricity.

Constructive solutions that are already in use in our factory:

Miller and shredder assembly V1

This first version of the miller/shredder assembly with cutting knives only on the rotative part of the miller that has the role to mill the intake product that comes inside the roller from the machine is shown in Figure 1.

Figure 1. Miller and shredder assembly V1 (Cenei Industrial Park)

Optimizing shredder blade design is critical for improving cutting efficiency and reducing energy consumption in waste processing (Nithyananth, 2014)

Miller and shredder assembly V2

In version 2 of the chopper (figure 2), the risk of jamming of the cutting assembly has been considerably reduced, by introducing a greater number of blades that ensure more efficient cutting. Also, by adding these additional knives, the time required for the chopping process has been reduced, compared to the previous version(V1)

Figure 2. Miller and shredder assembly V1 (Cenei Industrial Park)

Agricultural waste shredders play a pivotal role in enhancing the usability of organic material for energy production and composting (Kumar & Kumar, 2015)

New directions and paradigms in manufacturing

Further will refer to four main paradigms and directions in modern manufacturing that were applied for the modernization and optimization of our existing technological line at Cenei:

Reverse Engineering

Reverse engineering in manufacturing and engineering is used for a wide variety of reasons. By taking apart engineering equipment or a manufactured product and discovering the materials it is made from and how it works, we can help a business determine and improve production processes, enhance product effectiveness, and protect patents. (Cazan et al., 2023)

To remain competitive, the industry is continually searching for new methods to evolve its products. This need is addressed by introducing new reverse engineering, redesign methodology, formulating the customer needs, followed by reverse engineering, creating a functional model through teardowns. The functional model leads to specifications that match the customer's needs.

Reverse engineering has become the answer for industrial manufacturers seeking cost savings.

Reverse engineering serves as a bridge to shape engineering enabling the transformation of existing designs into innovative geometries suitable for modern manufacturing environments (Anwer & Mathieu, 2016)

Industry 4.0

The industry 4.0 proposal is considered a revolution in the industry, based on cyber-physical systems, and the fourth such revolution in history. This revolution succeeds in the first industrial revolution, steam (1700 – 1860); assembly line (1870-1969); automation (1969-2020). Industry 4.0 is scheduled from 2020 onwards (Kagermann et al., 2013).

Industries 4.0 was proposed and adopted as part of the German Government high-tech strategy action plan for 2020. The key promoters of Industry 4.0 are the Industry 4.0 working group and Platform Industries 4.0. They describe the industries 4.0 vision, the inherent basic technologies, and scenarios for its implementation (Kagermann et al., 2014, p. 5).

Subassemblies can be produced in smart fabrics, where robots and autonomous machines can be used to create parts for the assembly and the component head, thereby optimizing the manufacturing process to create efficiency and flexibility in production.

The Siemens approach to Industry 4.0 emphasizes the integration of cyber-physical systems and data-driven decision-making, paving the way for enhanced automation and smarter manufacturing processes (Cozmiuc & Petrisor, 2018)

Intelligent cloud manufacturing platforms play a key role in efficient resource sharing and collaboration within smart manufacturing networks, enhancing scalability and reducing production costs (Simeonea et al., 2018).

Use the software to simulate rotation and direct the virtual model to the sub-atomizer before physical production. At the same time, you can manage the product life cycle (PLM) to manage the evolution of your product along the entire route.

Data collected in manufacturing can be analyzed through big data analytics and machine learning to identify trends, understand processes and make data-driven decisions.

The depth space approach enables advanced human-robot collision avoidance, promoting safer and more efficient interactions in industrial settings (Flacco et al., 2012).

RESULTS AND DISCUSSION

The V2 chopper is designed to handle bales up to 1.20 meters in size. Its working process starts by feeding a bale of raw material, such as hay or straw, into the yellow main drum. This drum has an inclination of 20 degrees, which helps to direct the straw bale to the inner knives of the chopper. The drum has a special inner profile, with corners that have the role of guiding the bale on the correct path to the cutting knives inside the chopper.

The cutting and chopping process carried out by the V2 Shredder results in a granulation suitable for the subsequent stages of pellet or briquette production. This equipment optimizes the cutting process, preparing the raw material for use in the production line.

The rotation of the drum nr. 1 from figure nr. 3 and that of the cutting knives are reversed, that is, the drum rotates clockwise, while the knives nr 2 from figure nr. 3 rotate in the opposite direction, so that they can hook and cut the straw from the bale roll. The average time to cut and chop a bale is about 8-12 minutes. This time interval is due to the accumulation of approximately 2.5 cm of cut material in each rotation of the drum. The drum registers about 7-12 rotations per minute, which means a speed of about 15 cm per minute.

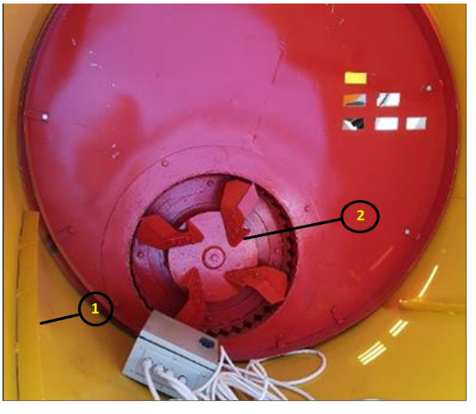

Figure 3. Miller and shredder assembly V2 (Cenei Industrial Park)

The rotation of the assembly consists of cutting knives, the shredding system and the blades have a speed of up to 1500 rpm, which generates a strong air current. This air current has the role of facilitating the suction process, thus contributing to the efficient evacuation of the processed material. This efficiency is also enhanced by the presence of vanes on the knives and slots on the inner wall of the drum, which optimize the direction and flow of air in the process

After consultations with the design team from the company Eco Mihis and following the analysis carried out, as well as the results obtained, we made the decision to develop, manufacture and market a third version of the shredder, known as Variant 3. This variant represents a hybrid approach in design and has been developed using the concept of reverse engineering to bring significant improvements.

Table 1. Performance comparison between Shredder V1 and V2 based on fiber dimension, shredded material density, and operational efficiency

X1 material type	**Nominal rotation**		**Load rotation**		**Fiber dimension**		**Shredder density**	
	Shredder V1 [RPM]	Shredder V2 [RPM]	Shredder V1 [RPM]	Shredder V2 [RPM]	Shredder V1 [mm]	Shredder V2 [mm]	Shredder V1 [kg/m3]	Shredder V2 [kg/m3]
Empty	1500	1500	1500	1500				
Straw	500	500	500	500	120	100	12	16
Straw	1000	1000	994	995	80	62	18	25
Straw	1500	1500	1460	1480	60	48	45	31
Hay	1000	1000	1010	1020	75	63	16	20
Hay	1500	1500	1430	1450	54	46	19	26

As shown in Table 1, the V2 shredder significantly outperforms the V1 model in terms of fiber dimension and shredded material density. For example, when processing straw at 1500 RPM, the fiber dimension achieved by V2 is reduced to 48 mm compared to 60 mm for V1, while the shredded material density increases from 45 kg/m³ to 31 kg/m³. These improvements result in faster processing times and enhanced material flow, as the optimized blade design and additional cutting elements in V2 minimize material clogging and ensure consistent performance. Consequently, the V2 shredder achieves higher efficiency, both in terms of operational speed and material handling, addressing the limitations observed in the V1 design.

Reverse Engineering

The goal is to create a copy of the milling assembly so we can adapt it to all kinds of future situations that we encounter. In this case, drawings will be used where, for example, we have changed the assembly of the rotor where the cutting blades were. So in this case, for example, we can have a man that builds the machine in Bihor but we are a little far away from that City, and we won't need to buy the machine from there if we can build it here in Timisoara, we will have the plans of the machines and what it will be needed to build it and we can build it here, just by using the reverse engineering methods that will allow us to save time and money.

In our situation, using reverse engineering will help us to improve the old machine without the need to look for the drawings of the old one or so.

Industry 4.0

In an article published in 2016, Hermann et al. define Industry 4.0 as a collective term for the technologies of value chain organizations, and the components of Industry 4.0 are classified as Internet of the Things, Cyber-Physical Systems, Internet of Services and Smart Factory.Industry 4.0 will make it possible to gather and analyze data across machines, enabling faster, more flexible, and more efficient processes to produce higher-quality goods at reduced costs. In Cenei's Industry, the technician must load the shredder with material that is needed to obtain the raw material that has to be used in the next process

The technician from Cenei needs to have the raw material obtained after the process of milling so it can be ready to use in multiple cases. After that with the use of sensors, some sensors for reading pellets (the silo has reached such capacity (as defined), we disconnect the mill, through a microprocessor. The technician has nothing else to do only to put the straw in the mold. In case of it has not reached the optimum humidity, it is necessary to add more water, and when the composition achieved the optimum humidity for palletization (around 10%), send the raw material (through a hose to the pellet press), and turn on the pellet mold.

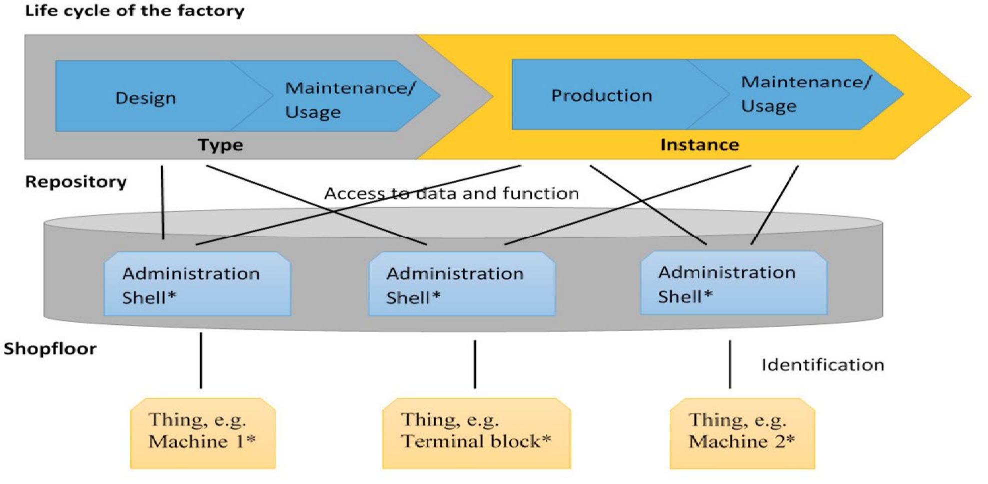

Figure 4. Life cycle of the factory

CONCLUSIONS

The main conclusion of this research is that pellets and briquettes are an extremely valuable energy source in the current context and have an extremely important role in the transition to a sustainable energy system. Technological progress is extremely fast and that is why it is imperative to update and implement innovative solutions in the production processes of solid biofuels in order to preserve the quality and competitiveness of the products.

During the evolution, the market requirements have registered a significant increase, and in this context, modern methods such as reverse engineering or Industry 4.0 can represent viable solutions for entrepreneurs who want to maintain their relevance and competitiveness. These innovative approaches provide the resources and technologies needed to meet changing market demands and adapt to the constantly evolving business environment.

The key factors in the transformation of production processes are digitization and the Industry 4.0 paradigm, which is rapidly moving towards Industry 5.0. These factors are essential for data analysis and for increased efficiency of the production process.

This paper presents four applications of an integrated cyber-physical system for cloud manufacturing. The developed functionalities for remote monitoring and control, distributed process planning, model-guided remote assembly, and active collision avoidance for human-robot collaboration can be wrapped as cloud services. Future work will include function improvement, testing, and embedding the four strategies into assembly plans so that the behavior of a robot matches the nature of a task for seamless human-robot collaborative assembly. The key factors in the transformation of production processes are digitization and the Industry 4.0 paradigm, which is rapidly moving towards Industry 5.0. These factors are essential for data analysis and for increased efficiency of the production process.

All benefits that are obtained by using cyber manufacturing, cloud manufacturing, reverse engineering, and industry 4.0 has an impact on improvement in the entire area of plant production and manufacturing of the optimizing of the production and design of a mold for pellets and briquettes.

Overall, the integration of Industry 4.0 technologies, reverse engineering, and advanced manufacturing solutions demonstrates a significant potential to revolutionize the production processes for shredding and pelletizing equipment. These innovations enable not only cost reductions and improved efficiency but also support the global shift towards sustainable energy systems by optimizing raw material usage. Future developments should focus on the continuous refinement of smart manufacturing paradigms and deeper exploration of data-driven decision-making, ensuring that these technological advances remain adaptable to the evolving demands of the industry.

The most important contribution of the paper is the opportunity of using new technologies like these four that are presented in this paper that have an impact on scalable manufacturing, manufacturing schedule duration, and costs that are needed to manufacture molds for pellets and briquettes.

ACKNOWLEDGEMENTS

This paper was written using data and results obtained through the project "Performance and excellence in the field of environment and renewable energy through modern cluster-type entities" with the acronym PEDMEREMC, SMIS code 138692, Project co-financed by the European Regional Development Fund through the Operational Program Competitiveness 2014 -2020.

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50. ACTUAL TASKS ON AGRICULTURAL ENGINEERING

Preliminary communication

ON MODERN ADDITIVE MANUFACTURING FOR SOME AGRO-INDUSTRIAL SECTOR COMPONENTS

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ABSTRACT

Modern manufacturing technologies have opened new opportunities for process optimisation in the agro-industrial sector, including the production of critical components used in emergency safety equipment. This paper analyses and compares conventional manufacturing technologies such as subtractive manufacturing or casting with the latest advancements in polymer- and metal-based additive manufacturing technologies. The analysis uses the example of fire sprinklers employed in emergency equipment as a case study, aiming to identify the advantages and limitations of these manufacturing technologies in terms of cost, dimensional accuracy, material durability and environmental impact. While traditional methods remain reliable for mass production, additive manufacturing proves to be particularly advantageous for customised and small-batch production, offering clear benefits in design optimisation, efficiency and production. The paper also highlights future research directions, which will involve the production of specific components through additive manufacturing technologies, intending to evaluate their dimensional characteristics, strength properties, hardness and structural analysis in order to assess their performance in real-world conditions. The integration of these technologies into the production of agro-industrial components could lead to more sustainable and efficient manufacturing, reducing the ecological impact of the production processes.

Keywords: *additive manufacturing, agroindustrial components, fire sprinklers, sustainability, production*

INTRODUCTION

In the agro-industrial sector, fire protection becomes essential to ensure the integrity and continuity of economic activities. Facilities that handle grains, process agricultural products such as vegetable oils or flour, store fertilizers and pesticides or produce biofuels, including pellets and briquettes, require the implementation of complex fire prevention systems. It follows that the use of fire sprinklers plays a crucial role in quickly and effectively limiting damage in the event of a fire, thus protecting stored production and ensuring the continuity of operations (Torvi, 2003).

Studies indicate the effective use of fire sprinklers in processing plants and large storage units, where risks are amplified by the density of combustible materials. Tanklevskiya et al. (2017), for instance, emphasise automatic sprinklers in processing and storage facilities, pointing out their quick fire suppression capabilities, that reduce loss of material as well as enhance safety. Applications in agro-industrial storage with restricted airflow may benefit from sector-specific sprinklers that are actuated by temperature monitoring, can be adjusted for ventilated conditions, discussed by Ingason et al. (2022) in settings like tunnels. Trapp and Rangwala (2015) show how in-rack sprinklers can be used to prevent fire spread in big warehouses (this technique can also be used in agro-industrial facilities that hold dense or flammable organic materials). In large-scale agricultural storage (where prompt suppression is vital) advanced methods like dynamic electronic activation bring the minimisation of response times and the maximisation of water consumption (Tanklevskiya et al., 2017).

This study reviews the manufacturing technologies for fire sprinklers, as a comparison between traditional methods like casting and subtractive manufacturing and recent advancements in polymer- and metal-based additive manufacturing. The findings demonstrate that integrating advanced manufacturing techniques into agro-industrial applications can help sustainability and reduce ecological impact of production processes.

MATERIALS AND METHODS

Firstly, a summary of the two main fire sprinkler production processes - conventional manufacturing and additive manufacturing - was conducted, and important findings were recorded.

To evaluate the advantages and disadvantages of these technologies in terms of production cost, dimensional accuracy, material resilience, and environmental impact, a review of the specialist literature was carried out in the second phase.

Based on the conclusions, thermal simulations were performed for four materials using Fusion 360 by Autodesk. A series of measurements and tests were also proposed for manufacturing fire sprinklers through additive technologies in order to validate their performance.

Conventional manufacturing technologies for fire sprinklers

The literature provides great details about the technological processes used for manufacturing fire sprinklers (surface treatments, casting, machining, and advanced numerical modelling to improve durability and performance). The first step in production is casting the main parts, such the frame and deflector, out of copper alloys like bronze, which are selected for their ability to withstand high temperatures and corrosion. After that, these raw materials are turned and milled to reach exact measurements and tolerances, and the deflector is further shaped for the best possible water dispersion. The glass bulb, which functions as a heat sensor, is included into the frame during assembly. In the end, to guarantee long-term durability, especially in demanding conditions, metal components are coated with anti-corrosion coatings, such as chrome plating (Zalosh, 2018; Jones and Bartle, 2021).

Precision forms and resilience to high temperatures are achieved through casting, while machining improves dimensions and guarantees component tightness, both of which are essential for system functionality. Bøe et al. (2024) and Kostka et al. (2023) speak about the robustness of materials made by casting, which can sustain high levels of mechanical and thermal stress. From Khan et al. (2023) is found that anti-corrosive treatments are essential for preventing metal parts from deteriorating in high-humidity and industrial settings. When combined, these technologies improve flow control and spray accuracy, making fire prevention more effective in a variety of settings.

Additive manufacturing technologies for fire sprinklers

Additive manufacturing technologies for fire sprinkler production focus on using polymeric and metallic materials. Their main purpose is to enhance durability, thermal performance and bring customisation. Ko et al., 2022 present that heat-resistant polymers are employed to create lightweight, efficient components, with corrosion-resistant layers which helps to sprinkler lifespan in high-humidity environments. On the metallic side, from Xu et al. (2018) or Kumar and Sharma (2024) it was found that laser sintering and powder fusion technologies allow for precise, durable structures from stainless steel and copper alloys, which are capable of withstanding extreme thermal stresses.

An area of innovation is represented by the integration of additive manufacturing with a CFD (Computational Fluid Dynamics) modelling to optimise spray patterns and water flow (Myers et al., 2018). Additively manufactured components tailored through CFD enhance fire suppression by (customisation of spray distribution to building-specific needs, plus flexibility beyond conventional methods). Research in hybrid materials combining polymers and metals has shown promise in improving mechanical strength and cooling efficiency. Studies by Mostofi et al. (2024) demonstrate that layered structures contribute to effective cooling and durability. Additionally, additive technologies enable the integration of sensors for real-time monitoring, which is an optimisation of the sprinkler activation based on environmental conditions (Khan et al., 2023).

Additive manufacturing enhances fire sprinkler design through innovative materials, precise engineering, smart solutions overall. Additive manufacturing sets new standards for safety, efficiency in diverse fire suppression scenarios.

RESULTS AND DISCUSSION

A synthesis of the advantages and limitations of fire sprinkler manufacturing technologies, based on articles published in the last five years, is presented in Table 1.

This analysis provides an in-depth understanding of the manufacturing processes used in fire sprinkler systems by highlighting both the benefits and drawbacks found in the literature.

For fire sprinklers, a set of validation tests is essential to ensure reliability, durability and effectiveness in fire suppression scenarios. To validate the sprinkler prototypes obtained through 3D printing technologies, a series of thermal, mechanical analyses and tests were conducted to observe how well they will perform in scenarios that are comparable to actual use.

Table 1 Advantages and limitations of fire sprinkler manufacturing technologies

	Advantages	Limitations
Cost Efficiency	Design optimization (using for instance genetic algorithms) reduces manufacturing time and associated costs (Chaudhary et al., 2024). Additive technologies allows cost reductions for small batches, customized designs, reduced material waste (Liu et al., 2020).	Material costs and initial investments in 3D printers are high (Van Coile et al., 2023). Increase total costs because of the specialized knowledge needed and the software requirements (Chaudhary et al., 2024).
Dimensional Accuracy	Numerical optimisation improves droplet size uniformity and water flux, enhancing sprinkler dimensional accuracy (Wang et al., 2024). Conventional processes like casting ensure consistency for standardised parts (Park et al., 2023).	Achieving high dimensional accuracy in complex geometries is challenging, may require multiple iterations, adjustments, that will increase production time and costs (Kim et al., 2023). Material variability may affect product consistency and accuracy in additive processes (Park et al., 2023).
Material Durability	Additive manufacturing allows for using advanced materials like composite alloys and high-performance polymers (Chaudhary et al., 2024). Conventional technologies are well-established for producing robust and reliable components (Park and Ko, 2023).	The selection of materials that can withstand high temperatures and mechanical stresses while maintaining durability can be limited and expensive. During time passing, exposure to harsh environmental conditions can degrade the materials used in sprinklers, reducing their effectiveness (Kim, 2024).
Environmental Impact	The optimization of sprinkler designs to achieve uniform water distribution can minimize water wastage, so there will be a reduced environmental impact for fire suppression systems (Park et al., 2023). The use of additive manufacturing technologies can potentially reduce material waste and energy consumption during production (Wang et al., 2024).	Although optimized designs can reduce water wastage, the production processes for advanced materials and technologies can have a significant environmental footprint (Wang et al., 2024). The disposal and recycling of defective or outdated sprinkler components may contribute to pollution if not managed properly (Van Coile et al., 2023).
Performance in Fire Scenarios	Numerical simulations have shown that optimised sprinkler systems can effectively control fire spread, reduce temperatures, increase evacuation times, thereby enhancing overall fire safety (Chiu et al, 2023). Experimental studies demonstrate that sprinklers optimised through additive manufacturing can improve response in complex fire scenarios (Kim et al., 2023).	The effectiveness of sprinkler systems can be influenced by various factors such as water pressure, nozzle design and the specific fire scenario, which may not always be predictable (Kim, 2024). In certain conditions, such as freezing temperatures or environments with sensitive goods, traditional sprinkler systems may not be suitable, necessitating alternative solutions (Kim, 2024).

Conventional manufacturing technologies for fire sprinklers

In the first stage, the process of components' analysation which were manufactured using conventional technologies involved a detailed examination of their technical specifications and geometry, in order to produce an accurate digital model.

To start this procedure, the data sheets of a chosen component (Figure 1) were used, which provided important information about the characteristics. Based on this data, a three-dimensional model of the component was created using Fusion 360 from Autodesk (Figure 2). After completing the 3D model, the optimization stage for additive manufacturing was initiated. This process involved a detailed analysis of the model's structure to adapt the design to meet the specific requirements of the selected 3D printing technologies.

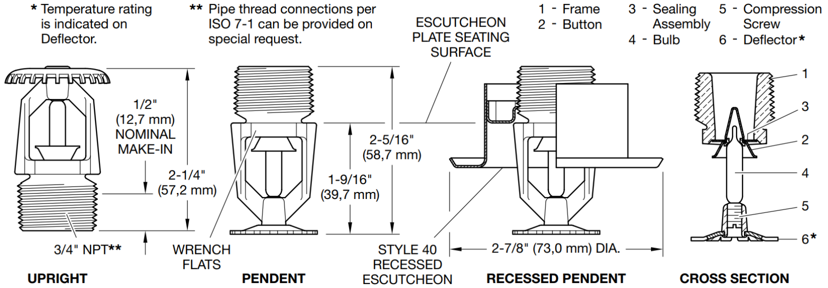


Figure 1. Series TY-B Upright (TY4151) and Pendent (TY4251) Sprinklers, with 8.0 K-Factor, 3/4 Inch NPT, Standard Response (Tyco Fire Products, 2023)

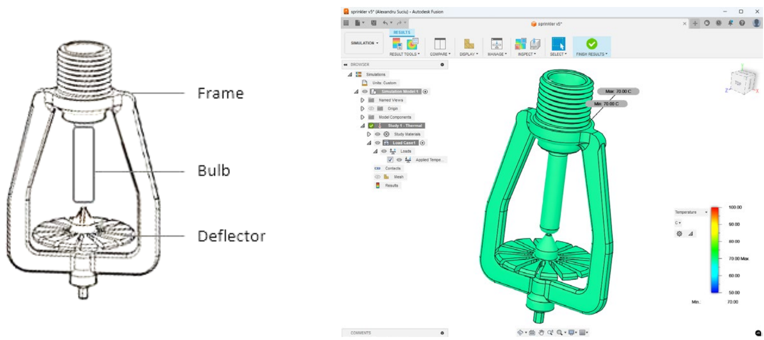
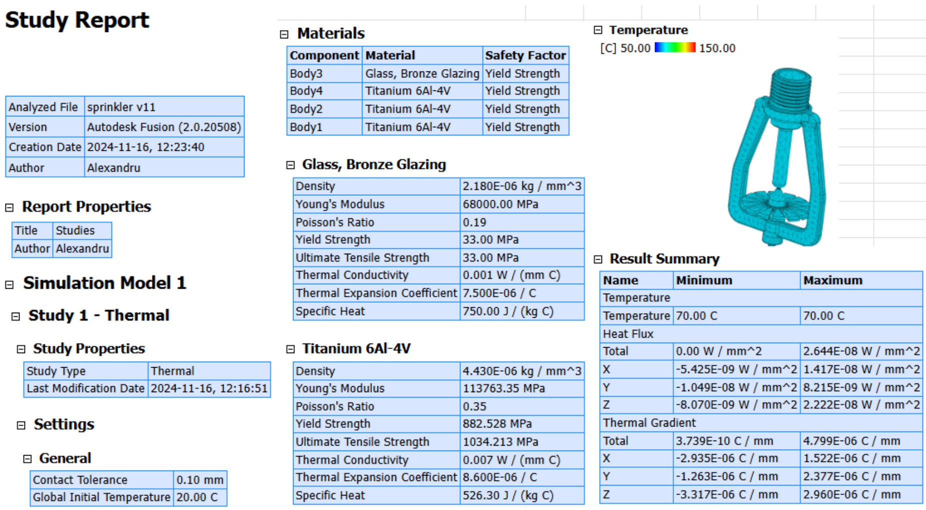


Figure 2. Schematic representation of the fire sprinkler design for additive manufacturing

Metal-based additive manufacturing technologies

Two types of metallic materials were selected: ENAW 6060-O aluminium alloy and Ti-6Al-4V titanium alloy, which were considered suitable for manufacturing sprinklers. Thermal simulations were conducted for these two materials using Fusion 360: in Figure 3 the titanium alloy at 70°C, in Figure 4 the aluminium alloy at 70°C.



Study Report

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Author	Alexandru

Report Properties

Title	Studies
Author	Alexandru

Simulation Model 1

Study 1 - Thermal

Study Properties

Study Type	Thermal
Last Modification Date	2024-11-16, 12:16:51

Settings

General

Contact Tolerance	0.10 mm
Global Initial Temperature	20.00 C

Materials

Component	Material	Safety Factor
Body3	Glass, Bronze Glazing	Yield Strength
Body4	Titanium 6Al-4V	Yield Strength
Body2	Titanium 6Al-4V	Yield Strength
Body1	Titanium 6Al-4V	Yield Strength

Glass, Bronze Glazing

Density	2.180E-06 kg / mm^3
Young's Modulus	68000.00 MPa
Poisson's Ratio	0.19
Yield Strength	33.00 MPa
Ultimate Tensile Strength	33.00 MPa
Thermal Conductivity	0.001 W / (mm C)
Thermal Expansion Coefficient	7.500E-06 / C
Specific Heat	750.00 J / (kg C)

Titanium 6Al-4V

Density	4.430E-06 kg / mm^3
Young's Modulus	113763.35 MPa
Poisson's Ratio	0.35
Yield Strength	882.528 MPa
Ultimate Tensile Strength	1034.213 MPa
Thermal Conductivity	0.007 W / (mm C)
Thermal Expansion Coefficient	8.600E-06 / C
Specific Heat	526.30 J / (kg C)

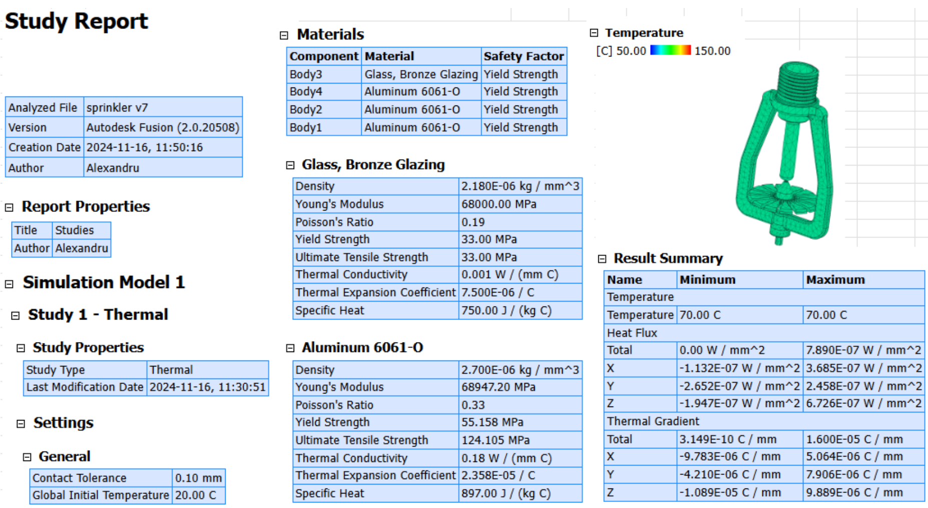
Temperature

[C] 50.00 150.00

Result Summary

Name	Minimum	Maximum
Temperature		
Temperature	70.00 C	70.00 C
Heat Flux		
Total	0.00 W / mm^2	2.644E-08 W / mm^2
X	-5.425E-09 W / mm^2	1.417E-08 W / mm^2
Y	-1.049E-08 W / mm^2	8.215E-09 W / mm^2
Z	-8.070E-09 W / mm^2	2.222E-08 W / mm^2
Thermal Gradient		
Total	3.739E-10 C / mm	4.799E-06 C / mm
X	-2.935E-06 C / mm	1.522E-06 C / mm
Y	-1.263E-06 C / mm	2.377E-06 C / mm
Z	-3.317E-06 C / mm	2.960E-06 C / mm

Figure 3. Thermal simulation for Ti-6Al-4V material at 70°C



Study Report

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Creation Date	2024-11-16, 11:50:16
Author	Alexandru

Report Properties

Title	Studies
Author	Alexandru

Simulation Model 1

Study 1 - Thermal

Study Properties

Study Type	Thermal
Last Modification Date	2024-11-16, 11:30:51

Settings

General

Contact Tolerance	0.10 mm
Global Initial Temperature	20.00 C

Materials

Component	Material	Safety Factor
Body3	Glass, Bronze Glazing	Yield Strength
Body4	Aluminum 6061-O	Yield Strength
Body2	Aluminum 6061-O	Yield Strength
Body1	Aluminum 6061-O	Yield Strength

Glass, Bronze Glazing

Density	2.180E-06 kg / mm^3
Young's Modulus	68000.00 MPa
Poisson's Ratio	0.19
Yield Strength	33.00 MPa
Ultimate Tensile Strength	33.00 MPa
Thermal Conductivity	0.001 W / (mm C)
Thermal Expansion Coefficient	7.500E-06 / C
Specific Heat	750.00 J / (kg C)

Aluminum 6061-O

Density	2.700E-06 kg / mm^3
Young's Modulus	68947.20 MPa
Poisson's Ratio	0.33
Yield Strength	55.158 MPa
Ultimate Tensile Strength	124.105 MPa
Thermal Conductivity	0.18 W / (mm C)
Thermal Expansion Coefficient	2.358E-05 / C
Specific Heat	897.00 J / (kg C)

Temperature

[C] 50.00 150.00

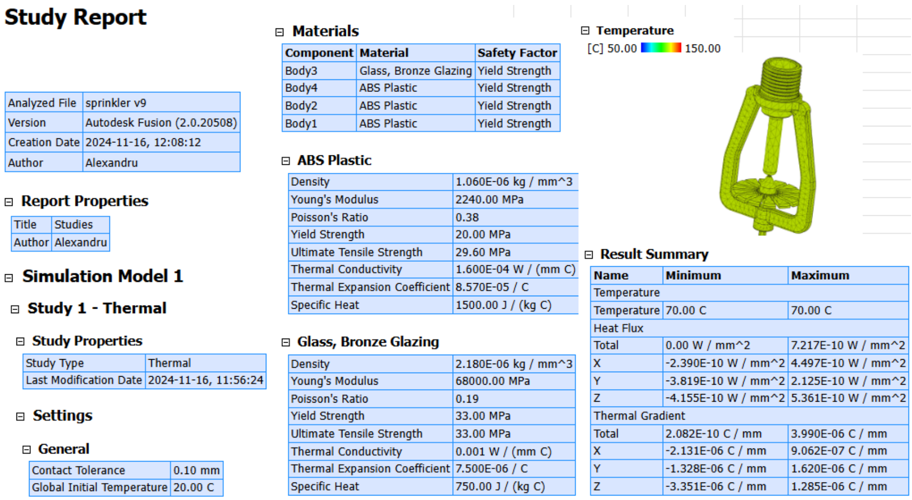
Result Summary

Name	Minimum	Maximum
Temperature		
Temperature	70.00 C	70.00 C
Heat Flux		
Total	0.00 W / mm^2	7.890E-07 W / mm^2
X	-1.132E-07 W / mm^2	3.685E-07 W / mm^2
Y	-2.652E-07 W / mm^2	2.458E-07 W / mm^2
Z	-1.947E-07 W / mm^2	6.726E-07 W / mm^2
Thermal Gradient		
Total	3.149E-10 C / mm	1.600E-05 C / mm
X	-9.783E-06 C / mm	5.064E-06 C / mm
Y	-4.210E-06 C / mm	7.906E-06 C / mm
Z	-1.089E-05 C / mm	9.889E-06 C / mm

Figure 4. Thermal simulation for ENAW 6061-O material at 70°C

Polymer-based additive manufacturing technologies

Polymer-based additive manufacturing technologies were also considered for the manufacture of fire sprinklers that are not directly exposed to very high temperatures. Two different plastic materials were selected for thermal simulations: ABS (Acrylonitrile Butadiene Styrene) and PEKK (Polyetherketoneketone reinforced with carbon fibres - HT-23). The results obtained for the temperature of 70°C are presented in Figure 5 for ABS and in Figure 6 for PEKK.



Study Report

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Author	Alexandru

Report Properties

Title	Studies
Author	Alexandru

Simulation Model 1

Study 1 - Thermal

Study Properties

Study Type	Thermal
Last Modification Date	2024-11-16, 11:56:24

Settings

General

Contact Tolerance	0.10 mm
Global Initial Temperature	20.00 C

Materials

Component	Material	Safety Factor
Body3	Glass, Bronze Glazing	Yield Strength
Body4	ABS Plastic	Yield Strength
Body2	ABS Plastic	Yield Strength
Body1	ABS Plastic	Yield Strength

ABS Plastic

Density	1.060E-06 kg / mm^3
Young's Modulus	2240.00 MPa
Poisson's Ratio	0.38
Yield Strength	20.00 MPa
Ultimate Tensile Strength	29.60 MPa
Thermal Conductivity	1.600E-04 W / (mm C)
Thermal Expansion Coefficient	8.570E-05 / C
Specific Heat	1500.00 J / (kg C)

Glass, Bronze Glazing

Density	2.180E-06 kg / mm^3
Young's Modulus	68000.00 MPa
Poisson's Ratio	0.19
Yield Strength	33.00 MPa
Ultimate Tensile Strength	33.00 MPa
Thermal Conductivity	0.001 W / (mm C)
Thermal Expansion Coefficient	7.500E-06 / C
Specific Heat	750.00 J / (kg C)

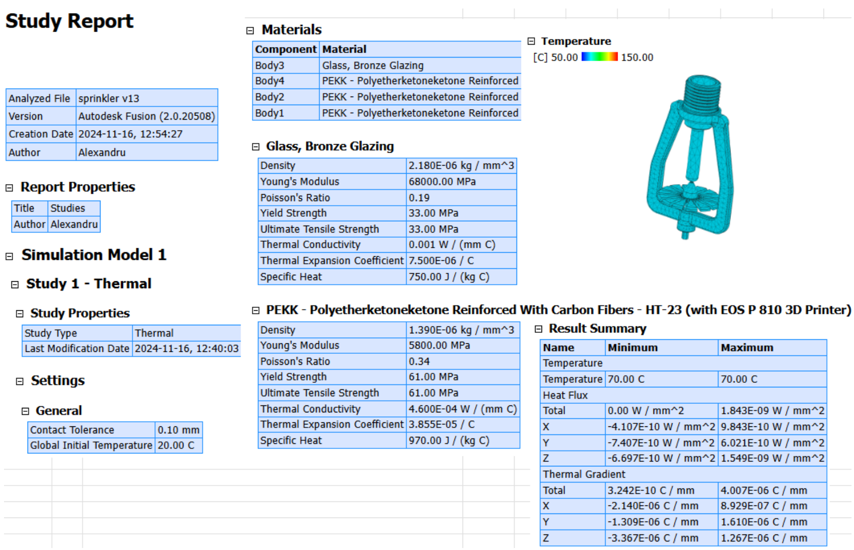
Temperature

[C] 50.00 150.00

Result Summary

Name	Minimum	Maximum
Temperature		
Temperature	70.00 C	70.00 C
Heat Flux		
Total	0.00 W / mm^2	7.217E-10 W / mm^2
X	-2.390E-10 W / mm^2	4.497E-10 W / mm^2
Y	-3.819E-10 W / mm^2	2.125E-10 W / mm^2
Z	-4.155E-10 W / mm^2	5.361E-10 W / mm^2
Thermal Gradient		
Total	2.082E-10 C / mm	3.990E-06 C / mm
X	-2.131E-06 C / mm	9.062E-07 C / mm
Y	-1.328E-06 C / mm	1.620E-06 C / mm
Z	-3.351E-06 C / mm	1.285E-06 C / mm

Figure 5. Thermal simulation for ABS material at 70°C



Study Report

Analyzed File	sprinkler v13
Version	Autodesk Fusion (2.0.20508)
Creation Date	2024-11-16, 12:54:27
Author	Alexandru

Report Properties

Title	Studies
Author	Alexandru

Simulation Model 1

Study 1 - Thermal

Study Properties

Study Type	Thermal
Last Modification Date	2024-11-16, 12:40:03

Settings

General

Contact Tolerance	0.10 mm
Global Initial Temperature	20.00 C

Materials

Component	Material
Body3	Glass, Bronze Glazing
Body4	PEKK - Polyetherketoneketone Reinforced
Body2	PEKK - Polyetherketoneketone Reinforced
Body1	PEKK - Polyetherketoneketone Reinforced

Glass, Bronze Glazing

Density	2.180E-06 kg / mm^3
Young's Modulus	68000.00 MPa
Poisson's Ratio	0.19
Yield Strength	33.00 MPa
Ultimate Tensile Strength	33.00 MPa
Thermal Conductivity	0.001 W / (mm C)
Thermal Expansion Coefficient	7.500E-06 / C
Specific Heat	750.00 J / (kg C)

PEKK - Polyetherketoneketone Reinforced With Carbon Fibers - HT-23 (with EOS P 810 3D Printer)

Density	1.390E-06 kg / mm^3
Young's Modulus	5800.00 MPa
Poisson's Ratio	0.34
Yield Strength	61.00 MPa
Ultimate Tensile Strength	61.00 MPa
Thermal Conductivity	4.600E-04 W / (mm C)
Thermal Expansion Coefficient	3.855E-05 / C
Specific Heat	970.00 J / (kg C)

Temperature

[C] 50.00 150.00

Result Summary

Name	Minimum	Maximum
Temperature		
Temperature	70.00 C	70.00 C
Heat Flux		
Total	0.00 W / mm^2	1.843E-09 W / mm^2
X	-4.107E-10 W / mm^2	9.843E-10 W / mm^2
Y	-7.407E-10 W / mm^2	6.021E-10 W / mm^2
Z	-6.697E-10 W / mm^2	1.549E-09 W / mm^2
Thermal Gradient		
Total	3.242E-10 C / mm	4.007E-06 C / mm
X	-2.140E-06 C / mm	8.929E-07 C / mm
Y	-1.309E-06 C / mm	1.610E-06 C / mm
Z	-3.367E-06 C / mm	1.267E-06 C / mm

Figure 6. Thermal simulation for PEKK reinforced material at 70°C

A comparative table was created using the information obtained about the four types of materials analysed (Table 2).

Given the information gathered, it was concluded that fire sprinklers can be manufactured from metallic materials, both titanium alloy and aluminium alloy, as well as from the plastic material PEKK reinforced with carbon fibres. ABS plastic material is suitable for non-critical, low-cost or prototyping applications where performance demands are minimal, meaning it does not meet the primary requirements for sprinkler manufacturing.

Table 2. Comparative analysis of the materials proposed for fire sprinkler manufacturing

Material	Strength	Weight	Temperature Resistance	Corrosion Resistance	Cost	Ease of Printing	Applications
Titanium Ti-6Al-4V	High	Medium	High	Excellent	High	Moderate	Industrial, high-risk environments
Aluminum 6061-O	Moderate	Light	Moderate	Good	Moderate	High	General-purpose systems
Plastic ABS	Low	Very light	Low	Moderate	Low	Very High	Prototyping, auxiliary parts
Plastic PEKK (reinforced)	High	Light	High	Excellent	High	Moderate	High-performance critical parts

The next step was the printing of prototypes using the selected materials. The manufacturing of these sprinklers through 3D metal printing was carried out using an MX-Mini by InssTek, which utilizes Direct Energy Deposition (DED) printing technology (Figure 7), chosen for its precision and ability to produce components with excellent mechanical properties and minimal material waste. This machine is in operation at National R&D Institute for Welding and Material Testing - ISIM Timișoara.

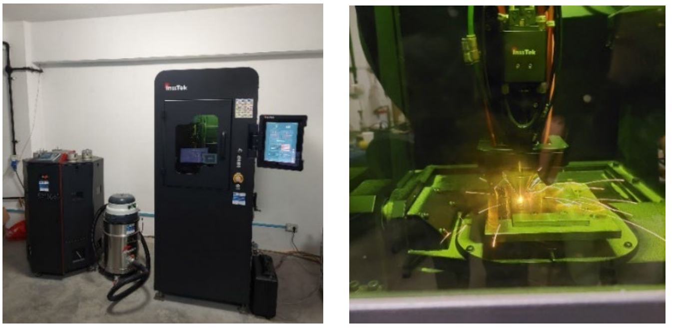


Figure 7. Metal-based additive manufacturing with DED

The polymer-based additive manufacturing technology selected for producing the fire sprinkler prototypes from reinforced PEEK was Fused Filament Fabrication (FFF) using a Bambu Lab X1C 3D printer (Figure 8), chosen due to its ability to process high-performance materials with enhanced mechanical and thermal properties at good speed rate. The printer used is from the R&D and manufacturing company AMI Machine Technology, Timișoara.

A series of tests was conducted to validate the sprinkler prototypes produced through 3D printing, focusing on geometric accuracy, structural integrity, hardness, abrasion resistance and mechanical properties. These evaluations were essential to ensure the prototypes' performance and safety in fire protection systems.

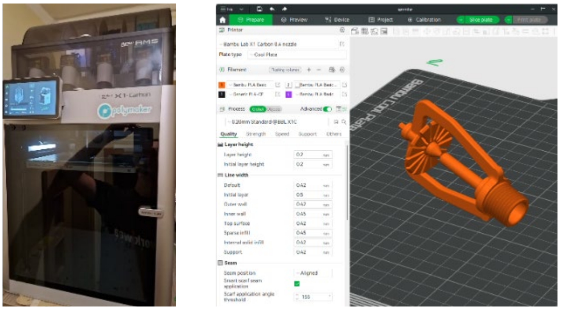


Figure 8. Polymer-based additive manufacturing with FFF

The methodology is outlined below:

Geometric measurements

Dimension and tolerance compliance was verified using a Hexagon DEA Global Lite 7.7.5 coordinate measuring machine, from Politehnica University of Timișoara (Figure 9), assessing essential dimensions such as lengths, diameters, flatness and symmetry.

Figure 9. Dimensional conformity and geometric analysis

Structural analysis, hardness and abrasion measurements

The prototypes were subjected to a detailed surface inspection to assess roughness and finish quality using the Ducom 3D Optical Profilometer (Figure 10a), which provided precise surface roughness measurements, and the Olympus BX 41M optical microscope for visual analysis. For hardness and abrasion resistance testing, the Wolpert 402MVD microhardness tester (Figure 10b) measured material hardness on a micro scale, while friction resistance was evaluated with the Ducom TR-20 Micro Tribometer (Figure 10c). These tests, particularly relevant for deflectors exposed to water jets, assessed surface wear under conditions of frequent contact and pressure. All analyses were conducted at the Politehnica University of Timișoara, Faculty of Mechanical Engineering.

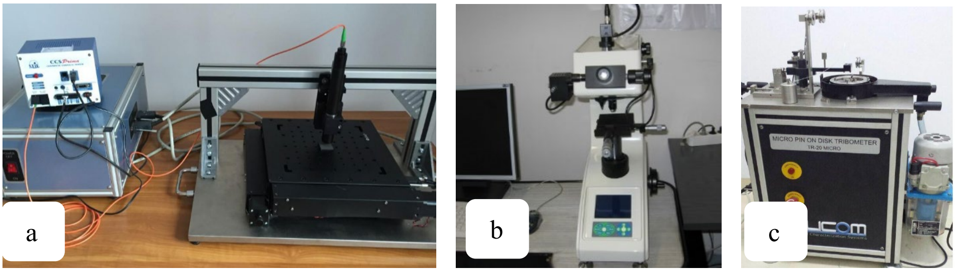


Figure 10. Roughness analysis **(a)**, evaluation of microhardness **(b)**, abrasion resistance **(c)**

Mechanical tests

The prototypes were then subjected to a series of mechanical tests to validate material and component strength. Tensile, compression, and bending tests were conducted using the LabTest 6.100 equipment from Figure 11a to measure deformation and failure points under controlled loads. Impact tests, simulating stresses during water jet activation, were performed with the LabTest CHK 450J-IA presented in Figure 11b. These tests were carried out at the specialised laboratory of ISIM Timișoara.

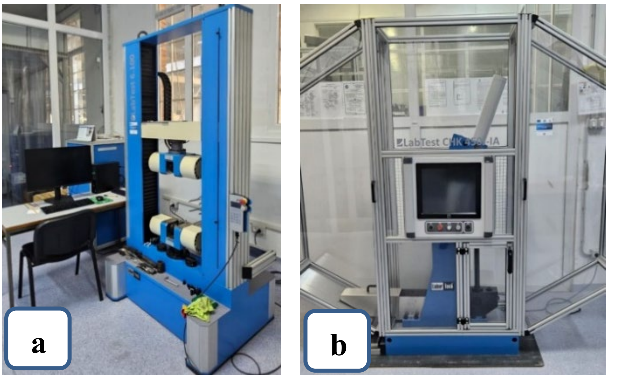


Figure 11. Evaluation of strength characteristics through mechanical testing

The results of the preliminary measurements and tests confirmed that the parts of the fire sprinklers produced through additive manufacturing meet the mechanical standards required for use in fire protection systems.

CONCLUSIONS

The research presented in this paper analysed conventional and additive manufacturing technologies for fire sprinkler production, focusing on their applicability to the agro-industrial sector. Conventional methods are reliable for mass production because they provide consistent performance and already meet all safety standards. However, their impact on the environment and the fact that they have limited adaptability to complex projects that need a different approach, as in the agricultural industry.

Additive manufacturing, including Direct Energy Deposition for metals and Fused Filament Fabrication for reinforced polymers, showed significant potential in producing prototypes with greater design flexibility and material efficiency. Despite promising results, challenges like scalability, material costs, and regulatory compliance must be resolved before adopting additive manufacturing for serial sprinkler production.

Thermal simulations and performance tests conducted on selected materials, including aluminium alloy EN AW 6060-O, titanium alloy Ti-6Al-4V and PEEK reinforced with carbon fibres, revealed that these materials meet the required standards for thermal and mechanical resistance under fire conditions. ABS was determined suitable only for non-critical or low-stress applications due to its lower performance metrics.

In agro-industrial facilities, such as those that process agricultural products or store potentially flammable products, the integration of advanced manufacturing technologies can bring clear benefits to fire prevention systems. Combining conventional, already reliable systems with additive manufacturing, which has the advantage of flexibility, can result in efficient, environmentally friendly fire sprinklers that minimize waste and conserve resources.

Future research will also focus on optimizing design and manufacturing parameters, as well as expanding the range of materials tested. Key tests will be carried out under controlled conditions, including fire temperatures and variable water pressures, in the Cenei Industrial Park, Timiș County, to validate the performance and safety of the prototypes.

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50. ACTUAL TASKS ON AGRICULTURAL ENGINEERING

Original scientific paper

ARTIFICIAL INTELLIGENCE IN AGRICULTURE – PERCEPTION OF THE RISKS IN HEALTH & SAFETY AT WORK

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ABSTRACT

The modernization of agriculture requires adaptation to change and proactive innovation to anticipate and manage disruptions in the work environment. This process involves integrating advanced technologies, such as Artificial Intelligence (AI), utilizing predictive models for crop growth and development, adopting sustainable farming practices, and implementing effective measures to mitigate the impact of climate change. The paper analyses the consequences of AI implementation in agriculture, related to specific OHS risks and possible effects. The proposed method analyses and compares the employee's perceptions towards introduction of different systems based on AI in agriculture, specific for different types of enterprises, in the west region of Banat area – Timis County. 35 agricultural enterprises were selected, different size, from 3 fields of activities, representative for agriculture (15 enterprises from CAEN code 011-cereal cultivation, 10 enterprises from CAEN code 012-orchards and 10 enterprises from CAEN code 014 – livestock production). For the study, a special questionnaire (8 questions) was distributed to 227 persons (19 in activity code 011, 84 in activity code 012, 113 in activity code 014 and 11 involved in other activities). Data from questioned people were statistically processed and analysed. The conclusions indicate that approximately 17% of employees have knowledge about AI, while more than 50% believe that, given the positive role of AI applications, it is essential to stay informed. Additionally, over 70% identified the "reduction of human workforce involvement" as a *negative impact of AI in agriculture, while 61% pointed to "affecting interpersonal relationships" as a concern.*

***Key words**: AI, OHS risk management system, perception and optimization*

INTRODUCTION

The use of advanced technologies in agriculture, that are already operational (e.g., unmanned aerial vehicles (UAV), (Anderegg et al., 2023), agricultural automation systems (Babanatis et al., 2018), robotics and autonomous robots (Tucu et al., 2010; Wang et al., 2023; Yang et al., 2023), big data (Wu et al., 2023), machine learning (Goodrich et al., 2023); deep learning (Li et al., 2023), cybersecurity, cloud computing etc.), have an impact on the development of the agricultural production chain (Klerkx et al., 2019) and generates high opportunity for the use of artificial intelligence (AI) in this industry. AI is becoming an increasingly common term in the agricultural sector, but there is still a significant degree of confusion regarding its true meaning and implications. This lack of clarity has given rise to various perspectives and concerns, with some believing that “AI is going in the wrong direction” or that “AI will completely take over all dirty, dangerous, and monotonous jobs,” sparking debates about its overall impact on the agriculture. There are some challenges for the use AI in agriculture as the workers underqualification, perception and their motivation regarding occupational health & safety (OHS) risks of accident in agriculture, especially the specific OHS management systems for SMEs (Crisan et al., 2017; Tucu A et al., 2021; Tucu A et al., 2023: Tucu et al., 2019). Many social and ethical issues are relevant for AI application, unique and varied impacts depending on different domains, types of AI being used and applications of AI (Ryan, 2022). Furthermore, the farmers need adequate environment and circumstances for using AI at work. There is a permanent pressure generated by special risks related with AI, especially stress, even the working environment is appropriate, and AI is implemented correctly (Stock and Gardezi, 2021). A lot of methods and procedures were elaborated for evaluate, avoid/ reduce stress (Gusetoiu and Tucu, 2012; Gusetoiu and Tucu, 2013) and develop Human-Centered AI (HCAI), as new approach to provide human control over, to align AI with human values, ethical principles and legal requirements (Shneiderman, 2020; Shneiderman, 2022).

The objective of this paper was to analyse perceptions of the AI concept and establish its connection to the activities of agricultural SMEs in the western region of Romania (Timiș County) to identify gaps in AI implementation that may require attention. Additionally, the final goal of the study was to identify and propose appropriate measures tailored to specific conditions.

METHODS

Based on the objectives of this study, the methodological flow is presented in figure 1, this includes 5 main steps. The questionnaire, including 4 general questions regarding dimensions of the enterprise (microenterprises (< 9 employees) noted 1, small (between 10-49 employees), noted 2 and middle (between 50-249 employees), noted 3), position (w-worker and m-manager), activity (1- crop production; 2- horticulture (fruit production); 3- livestock production; 4- Food Industry or/and others), and age, G (1- age under 18 years, 2- age between 18-24 years; 3- age between 25-39 years; 4- age between 40-64 years and 5- age over 65 years) and 6 questions regarding opinions about the use of AI in agriculture, was designed after studying more than 50 papers on the Web of Science from Clarivate Analytics platform. Question Q3 refers to familiarly concepts known: 1- Work Security, 2- Teleworking, 3- Factors of risk, 4- AI, 5- Internet of Things (IoT), 6- Precision Agriculture, 7- Management of the Occupational Health & Safety Work (MOHS), 8- OHS training, 9- Stress at work, 10- Overload at work. Question Q4 ask an answer regarding the confidence in the company's concern for AI with 5 levels: 1- extremely confident, 2- very confident, 3- moderate, 4- a little moderate, 5- not at all). Question Q5 ask to indicate factors with negative impact of AI in enterprise (1- Reduction of the human resource engaged in work, 2- Disruption of daily activities, 3- Pressure on employee productivity, 4- Reduced assistance time for solving tasks, 5- Loss of interest in typically human activities, 6- Low interest from management, 7- Complex work equipment and technologies, 8- Frequent changes to the work schedule, 9- The need to assimilate new, special, difficult knowledge, 10- Affecting interpersonal relationships). Question Q6 asks respondents to indicate most interesting consequences about AI (1- The apparent risk of work equipment, 2- Non-correlation of individual protective measures, 3- Ignorance regarding work equipment, 4- Frequent changes of tasks/ working conditions, 5- Stress at work, 6- Unclear or unstable work assignments, 7- Unclear regulations and responsibilities regarding work protection, 8- The attitude of colleagues towards risks for work protection, 9- Permanent and excessively rapid changes in work-related information, including volume, 10- Insufficient information about workplace health (dangers, protective measures, contamination etc.), under specific conditions), Question Q7 asks about the option on methods for protection considered to be effective (1- Adequate work instructions for the use of equipment, 2- The least possible use of artificial intelligence, only if there is no alternative, 3-Degrees of restrictions (measures) at the employee level regarding access to work equipment, 4- Use of adequate collective protection measures, 5- Knowledge/information regarding the risks when using artificial intelligence, 6- Specific training on work equipment, 7- Control of hierarchical heads (HSE manager, management, work inspector etc.). Question Q8 ask if the respondent consider himself is enough informed about applications of AI at workplace (1- yes, 2- no, 3- I am going to inform myself, 4- others).

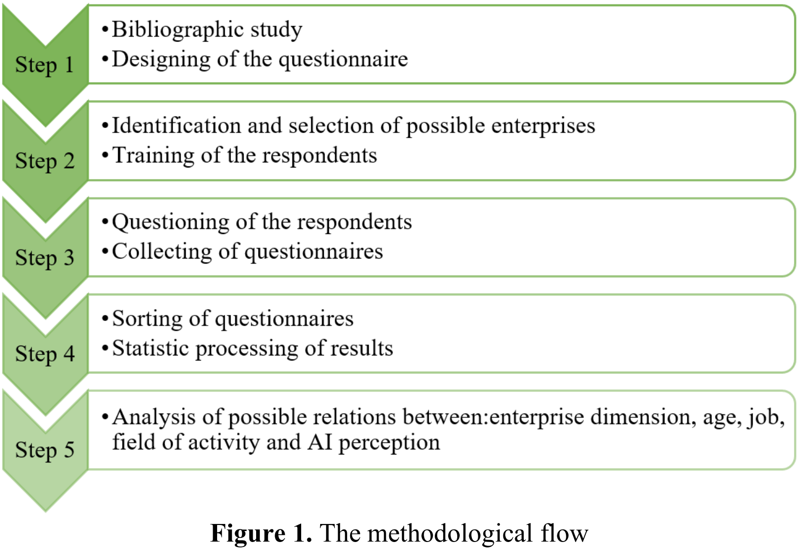

Figure 1. The methodological flow

In the next steps, 35 agricultural enterprises from 4 fields of activities, typical in agriculture from the western part of Romania (15 enterprises from national code of activities classification (CAEN), code 011-crop production (noted 1), 10 enterprises from CAEN code 012-fruit cultivation (noted 2), and 10 enterprises from CAEN code 014 – livestock production (noted3)), selected from different sizes), were selected for the questionnaires regarding AI perceptions. If a respondent had another activity, it was noted with 4. The questionnaires were distributed to 223 persons (20 in code CAEN 011, 81 in code CAEN 012 and 110 in code CAEN 014, and 12 from other activities). The results were processed for statistic analyse using Microsoft Excel and STATGRAPHICS. The statistical relevance was verified by ANOVA and Multiple Range Tests, if exists some influence due to enterprise size, field of activity, age and job on AI perception.

RESULTS AND DISCUSSION

Table 1 presents a sequence from centralized results of 227 answers, in Microsoft Excel.

Table 1. Sequence from centralized results of answers in Microsoft Excel

No	Enter-prise		Job	Age	Q3-Familiary concepts										Q4 - confi-dence					Q5- Negative impact										Q6- Consequences										Q7- Protection Eff.							Q8- Level Inf.			
	Dim	Act			1	2	3	4	5	6	7	8	9	10	1	2	3	4	5	1	2	3	4	5	6	7	8	9	10	1	2	3	4	5	6	7	8	9	10	1	2	3	4	5	6	7	1	2	3	4
1	1	w	3	4						1		1				1																															1			
2	1	w	3	4						1							1										1						1																1	
2	1	w	3	3									1			1				1															1						1								1	
2	1	w	4	4						1						1				1														1										1					1	
3	1	w	3	4	1		1	1	1			1							1	1																		1			1							1		
3	1	w	3	3	1		1					1							1			1								1					1	1					1					1		1		
3	1	w	3	4	1		1					1							1			1														1	1				1					1		1		
3	1	w	3	4	1		1					1	1											1												1					1					1				1
3	1	w	3	4	1		1					1							1			1														1	1									1		1		
3	1	w	3	4	1		1	1	1			1							1	1																		1			1							1		
3	1	w	3	4	1		1					1							1										1	1																1		1		
3	1	w	3	4	1		1					1					1							1												1				1							1			
3	1	w	3	3	1		1					1	1	1					1			1	1			1					1	1			1	1	1				1					1		1		
4	2	w	4	4			1	1	1			1				1				1																	1			1			1	1				1		
4	2	w	4	2	1	1	1	1	1		1	1	1	1		1						1		1		1		1	1			1		1				1	1	1			1	1	1	1		1		
4	2	w	4	2	1		1	1	1	1	1	1	1	1	1					1				1					1	1		1	1				1			1		1	1	1	1	1	1			
5	3	w	2	2	1		1			1	1	1	1	1			1			1		1		1			1	1	1					1				1		1								1		
5	3	w	2	3	1		1			1	1	1	1	1			1			1		1		1			1	1	1				1	1	1			1	1	1		1	1	1					1	

No.- Code number of enterprise, Dim.- dimension of enterprise, Act.- type of activity, Because 96.86% from respondents were workers, the influence of other work positions categories (managers, specialists) has not significant interests for the study.

The weight of answers, pWi, were calculated with next formula:

$$pWi = 100 * \frac{ni}{227} \tag{1}$$

where ni - the number of answers at specific question.

Given that, after centralizing and analyzing the responses, only a small percentage of respondents (5.4%) are active in other fields, and there were no participants under the age of 18 or over 65, these specific categories were not considered relevant for statistical processing and were therefore excluded from the final analysis. The results for the calculated weight of answers for Q3, Q4 and Q5 are presented in Table 2 and the results for the calculated weight of answers for Q6, Q7 and Q8 are presented in Table 3.

Table 2. Results of calculated weight of answers for Q3, Q4 and Q5

Fac-tors	**pWi at Q3-Familiary concepts, [%]**										**pWi at Q4 – confidence in AI, [%]**					**pWi at Q5- Negative impact, [%]**									
	1	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**1**	**2**	**3**	**4**	**5**	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**
PT	**84.8**	**13**	**67.3**	**17**	**30**	**25**	**40**	**85.7**	**47**	**17**	**1.3**	**11**	**35**	**37**	**17**	**70**	**0.9**	**22**	**7.2**	**45**	**3.1**	**12**	**13**	**26**	**61**
pMC	72.5	5.9	64.7	16	7.8	14	22	80.4	37	20	0	24	33	18	24	51	0	27	3.9	18	2	24	9.8	12	33
pSM	98.8	4.9	93.8	23	73	21	73	93.8	79	6	1.2	3.7	20	63	12	93.8	0	11	6.2	77	2.5	8.6	7.4	33	94
pMD	79.1	25	45.1	12	3.3	34	22	81.3	24	24	2.2	9.9	48	24	16	59.3	2.2	27	9.9	32	4.4	7.7	20	29	47
PT	**84.8**	**13**	**67.3**	**17**	**30**	**25**	**40**	**85.7**	**47**	**17**	**1.3**	**11**	**35**	**37**	**17**	**70**	**0.9**	**22**	**7.2**	**45**	**3.1**	**12**	**13**	**26**	**61**
pA1	85	15	70	20	10	15	25	85	20	25	0	15	35	40	10	65	0	25	15	30	5	15	15	25	55
pA2	96.3	0	90.1	21	65	16	86	92.6	79	7	1.2	1.2	22	64	12	91.4	0	20	1.2	79	4.9	4.9	14	47	91
pA3	78.2	21	50	11	5.5	30	8.2	81.8	27	18	0.9	14	45	19	20	57.3	0.9	24	11	24	1.8	15	12	12	42
PT	**84.8**	**13**	**67.3**	**17**	**30**	**25**	**40**	**85.7**	**47**	**17**	**1.3**	**11**	**35**	**37**	**17**	**70**	**0.9**	**22**	**7.2**	**45**	**3.1**	**12**	**13**	**26**	**61**
pV2	70.8	13	66.7	33	33	33	67	91.7	50	38	4.2	13	38	21	29	83.3	0	33	0	63	0	21	33	46	71
pV3	90.2	16	68.3	20	35	22	45	87.8	49	16	2.4	7.3	33	44	13	67.1	1.2	21	8.5	52	4.9	7.3	12	30	62
pV4	84.2	12	66.7	12	25	24	32	83.3	46	12	0	12	34	36	17	70.2	0.9	20	7	36	2.6	12	9.6	20	59

Analysing the results presented in table 2 can be observed that about 85% from questioned workers know the concept of Work Safety and OHS training, over 67% know about Risk Factors, 47% Stress at work, 40% Management of the Occupational Health & Safety Work (MOHS) and 30% about Internet of Things (IoT) (the most knowledge have workers form small enterprises (IoT is recognized by more than 73% of respondents, in contrast to Precision Agriculture, which is acknowledged by only 25%.

This discrepancy suggests that workers may obtain information primarily from media sources rather than specialized literature!)). The analysis of variance ANOVA confirmed that there isn't a statistically significant difference between the means of the 4 variables at the 95.0% confidence level, because the F-ratio was 1.17891, and the P-value of the F-test is greater than or equal to 0.05.

Table 3. Results of calculated weight of answers for Q6, Q7 and Q8

Fac-tors	pWi at Q6- Consequences, [%]										pWi at Q7- Protection Eff., [%]							pWi at Q8- Level Inf., [%]			
	1	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**1**	**2**	**3**	**4**
PT	**22**	**5.8**	**21**	**20**	**18**	**15**	**7.2**	**8.5**	**46**	**13**	**35**	**47**	**9.9**	**40**	**22**	**20**	**16**	**17**	**29**	**54**	**0.4**
pMC	24	3.9	27	25	7.8	18	14	16	25	7.8	49	24	9.8	20	24	25	22	16	41	47	2
pSM	22	6.2	15	4.9	15	8.6	7.4	11	74	16	21	70	2.5	73	16	17	14	1.2	15	84	0
pMD	22	6.6	22	30	26	19	3.3	2.2	32	13	40	40	16	22	26	19	15	32	35	32	0
PT	**22**	**5.8**	**21**	**20**	**18**	**15**	**7.2**	**8.5**	**46**	**13**	**35**	**47**	**9.9**	**40**	**22**	**20**	**16**	**17**	**29**	**54**	**0.4**
pA1	35	20	30	20	10	15	5	15	40	30	40	60	35	25	25	40	25	20	45	55	0
pA2	4.9	1.2	4.9	20	21	9.9	0	1.2	83	6.2	21	74	6.2	74	14	4.9	1.2	12	8.6	79	0
pA3	32	7.3	31	20	16	20	13	11	24	14	44	26	8.2	18	24	25	24	20	41	36	0.9
PT	**22**	**5.8**	**21**	**20**	**18**	**15**	**7.2**	**8.5**	**46**	**13**	**35**	**47**	**9.9**	**40**	**22**	**20**	**16**	**17**	**29**	**54**	**0.4**
pV2	17	0	25	33	42	17	0	4.2	54	8.3	58	42	17	54	33	17	13	21	46	33	0
pV3	16	4.9	23	16	16	16	7.3	7.3	46	15	30	52	9.8	44	21	15	12	26	22	54	0
pV4	28	7.9	18	19	15	13	8.8	11	44	13	33	46	8.8	35	19	25	20	11	32	59	0.9

Also, the analysis of variance ANOVA and Multiple Range Tests confirmed there isn't a statistically significant difference between the means of the 4 variables at the 95.0% confidence level, in the case of activity and age for answers at the Q3. This means that the classification presented previously was validated. As practical measures will be important to develop and educate the workers perception on teleworking, AI, precision agriculture and overload at work (In rural areas, it is common for work schedules not to be strictly followed!).

Regarding the confidence in the enterprise concern for AI (question Q4), 37% of respondents declared they are less than moderate (level 2 from 5), 35% moderate, 17% not at all, 11% very confident and 1.3% extremely confident. Similarly, the analysis of variance ANOVA and Multiple Range Tests confirmed there isn't a statistically significant difference between the means of the 4 variables at the 95.0% confidence level in the cases of enterprise size, field of activity and worker seniority. So, it will be important to increase the confidence of workers in actions of company to correct information regarding AI (trainings, presentations, stakeholders etc.), by adequate budgeting.

About the negative impact of AI in enterprise (Q5), more than 70% considered as negative factor of AI in agriculture `Reduction of the human resource engaged in work`, 61% appreciated as negative factor `Affecting interpersonal relationships`, 45% nominalized ` Loss of interest in typically human activities`, 26% `The need to assimilate new, special, difficult knowledge` and 22% `Pressure on employee productivity`. The other negative factors received 13% ` Frequent changes to the work schedule`, 12% `Complex work equipment and technologies`, 7.2% `Reduced assistance time for solving tasks`, 3.1% ` Low interest from management`, and 0.9% `Disruption of daily activities`. The same measures as Q4 will be a necessity.

For the most interesting consequences of AI (Q6), average 46% indicated `Permanent and too rapid change of work information`, including quantity (with accent in small enterprises, horticulture and age between 18-15 years), and almost a quarter from respondents indicated `The apparent risk of work equipment` (average 22%), `Ignorance of work equipment` (average 21%), `Frequent change of tasks/working conditions` (average 20%) and `Stress at work` (average 18%) , all with accent in microenterprises and small enterprises, crop production and horticulture, and age between 18-25 years or 40-64 years. One factor has 15% (`Unclear or unstable work task`, with accent in microenterprises from livestock production, age between 18-25 years), and the other received a level under 9%. A practical implication will develop new courses based on the AI used in agriculture and in universities. As method of protection effective (Q7), average 47% proposed `The least possible use of artificial intelligence, only if there is no alternative`, 40% proposed `Use of adequate collective protection measures` and 37% `Adequate work instructions for the use of equipment` (most options in small enterprises from horticulture, age between 18-39 years). Almost a quarter from respondents indicated next measures: average 22% `Knowledge/information regarding the risks when using artificial intelligence`, 20% `Specific training on work equipment` and `Control of hierarchical heads (HSE manager, management, work inspector etc.)`, (most options in microenterprises from crop production and age between 40-64 years). At question regarding the level of respondent's information about AI (Q8), more than a half (average 54%), considered necessary to go to inform themselves about AI in agriculture (more in small enterprises from horticulture, age between 40-64 years), average 29% considered are not informed and 17% considered they are informed on AI. Based on the last questions (Q6, Q7, Q8), it is essential to conclude that there is an urgent need to organize actions aimed at preparing workers in the field of AI applications and providing a fair presentation of the associated risks. The future applications must be based on a combination of human-centered AI and Industry 5.0, as-called Agriculture 5.0 (Holzinger et al., 2024) and respecting human values, ethical principles and legal requirements (especially regarding OHS), (Shneiderman, 2020).

CONCLUSIONS

Social factors and network effects play a fundamental role in adoption of AI technology in agriculture and represents an important challenge. The use of AI, digitalisation, precision agriculture or any other instruments must be mixed with human interaction and done with a good knowledge and undersanding.

In any similar analysis, the integration of advanced technologies such AI, needs to improve agricultural practices, technologies and policies based on new concept Industry 5.0, also known as 'human-centered industry (HCAI)'.

Practically, will be necessary to develop a new approach which provides the control of workers in agriculture over the AI technologies and align AI with human values, ethical principles and legal requirements (especially regarding OHS). The present study serves as evidence of the current state and future needs of agricultural SMEs in the western region of Romania.

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50. ACTUAL TASKS ON AGRICULTURAL ENGINEERING

Expert paper

INNOVATION AND TECHNOLOGY TRANSFER: PERSPECTIVES FROM THREE CASE STUDIES

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ABSTRACT

In recent decades, the activity of innovation and technological transfer has gained stable and important ground in the competitive struggle.

As far as agricultural technology is concerned, a plan drawn up in the European Union to verify the efficiency of the use of various renewable raw materials is being prepared, which classifies the types of technology transfer facilities. In this case, industrial, scientific and technology parks, incubators, clusters and liaison offices with the agricultural industry are analyzed. In ex-communist countries, legislative frameworks have had a major impact on the transformation of organizational entities. A legislative framework has funds have been set aside specifically for the conversion of technological transfer engineering, agriculture field included, and as a result, three case studies - Tim Science Park, the Innovation Cluster WESTTIM, and the Cenei Technology Park - will be examined, that were financed from public funds. European Union programs Horizon and the UN Sustainable Development Goals granted the innovation at EU level, at the national level, technology transfer and new business startup were facilitated by Start Up grants. A software that calculates the ash and calorific value was developed in the INOMAT project, and it will be presented in this paper.

Keywords: *Agricultural engineering, Industrial parks, Ecosystem, Clusters, Technological Park*

INTRODUCTION

Innovation and technology transfer have become fundamental drivers of economic competitiveness in Romania and across the European Union (EU). Over the past decade, legislative frameworks have been updated to provide better classification and support for technology transfer entities, reinforcing their role in organizational transformation and knowledge exchange (Applicant's Guide, Specific Conditions for Accessing Funds - Supporting Innovation Entities, 2018).

Universities play a crucial role in fostering public-private partnerships, facilitating the transfer of knowledge and technology between research institutions and industry. Channels such as foreign investments, licensing agreements, and corporate collaborations have proven essential in accelerating technological advancements across Europe. Notably, enterprises in Southeast Europe are transitioning towards distributed architectures, requiring advanced tools and development strategies to stay competitive (Curaj et al., 2022).

This paper examines the impact of newly established technological transfer entities, analysing three case studies that have been influenced by specific legislative frameworks (Official Gazette No. 643, August 30, 2002). The study further explores predictive models for start-up sustainability, leveraging artificial neural networks to assess the financial viability of firms participating in technology transfer initiatives. Data from the National “Start-Up Nation” program is used to generate statistical insights into the success rate of newly funded companies.

The case studies analysed are:

- TIM Science Park, the first scientific and technological park in Eastern Europe.
- INO-MAT, a start-up project focused on renewable energy and industrial optimization, explored in research by Suta et al. (2021) and Matei L. G. et al. (2023).
- WESTTIM Innovation Cluster, specializing in environmental performance and renewable energy, with a CDI project aimed at enhancing regional competitiveness (Enachi M. et al., 2021, Feier at al., 2022).

Additionally, this paper presents a software tool developed within the INO-MAT project, designed to calculate calorific value and ash content in biomass-based fuel production. This technological innovation contributes to optimizing pellet and briquette manufacturing, aligning with sustainability goals (Maris, 2022).

By exploring these case studies, this research aims to highlight the role of technology transfer entities in driving economic growth, innovation, and environmental sustainability. Furthermore, it underscores the necessity of legislative support, funding mechanisms, and interdisciplinary collaboration in fostering long-term success in the field of technology transfer.

MATERIALS AND METHODS

This study employs a systematic literature review on technological transfer entities, utilizing the Web of Science core collection database as a primary research source. The methodological approach includes both qualitative and quantitative analyses to assess the impact of innovation hubs, industrial parks, and clusters on economic growth and sustainability.

A statistical study was conducted to evaluate agricultural engineering advancements in South-Eastern Europe, focusing on three case studies: TIM Science Park, the WESTTIM Innovation Cluster, and Cenei Technology Park. The study references key literature, including the EU Guide on Accessing Funds for Technological Transfer and the Guide to Cost-Benefit

Analysis of Investment Projects (2014-2020), to assess the effectiveness of various funding mechanisms in fostering innovation (Cazan et al., 2023).

To analyse the financial stability and long-term sustainability of start-ups benefiting from technological transfer programs, a database was created in Excel. This database tracks the status of companies that received grants under the "Start-Up 2018" program, enabling a comprehensive assessment of their business performance and financial recovery processes.

The research methodology follows a structured approach, as outlined in Table 1, which details key aspects such as feasibility studies, economic environment assessment, investment climate analysis, and business planning strategies (Săvescu, 2015).

Table 1. Planning the chosen methodology in this paper (Săvescu, 2015)

The study	Feasibility studies	Statistics
The project	Grants	Tax facilities
Project planning	The business plan	The marketing plan
Project launch	Project management	Technology adaptation
Business climate	The economic environment	The investment climate
Technological transfer	The search for technology	Innovation continues

Predictive Analysis Using Artificial Neural Networks

To further enhance the evaluation of start-ups' financial stability, a neural network model was developed to forecast potential bankruptcy risks. This model is a classification-based pattern recognition system, implemented using MATLAB's Neural Network Toolbox.

The network topology consists of: an input layer with four variables: revenue return rate (X1), coverage rate of liabilities with cash flow (X2), asset leverage (X3), and payment period of obligations (X4); one to three hidden layers with 10 to 20 neurons per layer; an output layer with a single prediction variable, indicating the likelihood of bankruptcy.

Figures 1, 2, and 3 illustrate the optimization of the network's accuracy based on the number of neurons per layer and hidden layers (Pirtea M. et al., 2015).

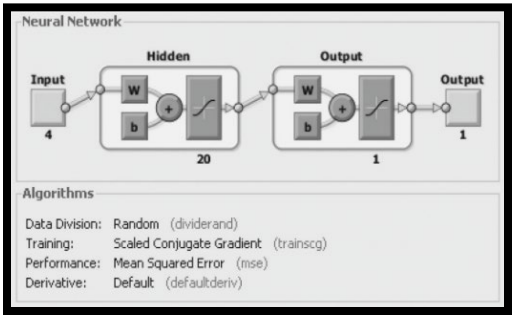

Figure 1. Topology of an Artificial Neural Network for bankruptcy forecasting (Pirtea M., et al, 2015)

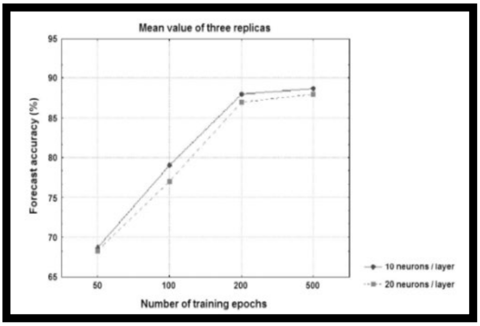

Figure 2. Forecast accuracy versus the number of neurons per layer (Pirtea M., et al, 2015)

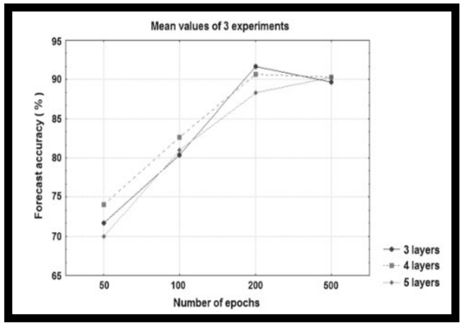

Figure 3. Forecast accuracy versus the number of layers (Pirtea M., et al, 2015)

A similar model was specifically applied to a pellet producer within the INO-MAT project, revealing several critical scenarios:

- Inconsistent raw material availability affecting production quality.
- Producers modifying pellet formulations based on available resources.
- The necessity of balancing calorific value and ash content for optimal product performance.
- The need for specialized expertise in calorific value calculations.

To address these challenges, an Excel- and Statgraphics-based software tool was developed, enabling accurate analysis of pellet compositions and calorific performance (Figure 4). This tool also provides recommendations for raw material selection to optimize both heat efficiency and environmental impact.

	Material 1	Material 2	Material 3	Material 4	Material 5
What raw material do you want to use? (choose a maximum of 5)	**Apple tree (branches)**	**Potatoes (plant)**	**Hazelnut (shells)**	**Charcoal (of plant origin)**	**Sunflower (straw)**
How many kg of each component will you use?	**20**	**30**	**10**	**10**	
The percentage of each component in the recipe will be	28,57%	42,86%	14,29%	14,29%	0,00%
The calorific value of each individual component is	0	19,13	17,51	17,51	16,9
The residual ash of each individual component is	0	1,8	12	12	2,1

The calorific value of the selected mixture is 13,20 MJ/kg.

The residual ash of the mixture is 4,2 %.

Figure 4. Excel software tool demonstration

Technological Infrastructure and Equipment

The studies analysed (Suta et al., 2021, Maris, 2022, Bejerita et al., 2023) also examine the technological infrastructure necessary for sustainable pellet and briquette production. Key equipment used are:

- A technological production line for pellets and briquettes.
- A hobby pellet press for experimental testing.
- A combustion stove for performance assessment.
- Measuring instruments for evaluating calorific values and ash content.

The selection of pellet boilers was based on room dimensions and insulation levels, ensuring optimized energy consumption. The study incorporated industry standards, such as 60W/m³ for poorly insulated spaces and 40W/m³ for well-insulated areas, to determine appropriate heating solutions.

A correlation was found between various raw materials and the produced pellets, influencing both ash quantity and calorific value. The behaviour of pellet boilers is a significant factor, as it relates to the amount of heat that needs to be transmitted and provided. In this instance, a calculation formula found in the specialized literature can be used to determine the boiler's consumption:

$$C = \frac{P}{\eta} * Hu \qquad (1)$$

where C is fuel consumption in kg/h, P – the boiler power in kW, η - the efficiency of the boiler in % and Hu - the calorific value of the fuel in kWh/kg.

CASE STUDIES FOR INNOVATION AND TECHNOLOGY TRANSFER IN ACTION

The sustainable development of innovation in the EU is strongly linked to legislative norms, with the European Institute of Innovation and Technology (EIT) enhancing Europe’s innovation capacity. The long-term thematic partnerships in knowledge and innovation communities are crucial for ensuring business viability, particularly in economic crises. However, in Romania, research and development (R&D) investments remain below the European average, limiting the impact of innovation on economic and social growth.

Despite the challenges, data from 2019-2024 reveals a 76.55% survival rate among 921 analysed startups, exceeding the national average. Many of these startups were part of the "Start-Up 2018" funding program, financed by the Romanian state. Due to prolonged evaluation processes, many companies received financial agreements in 2019, with some extending to 2021. However, by 2024, financial difficulties led to 216 firms having their non-repayable aid reclaimed along with penalties, as presented in Table 2.

Table 2. Start Up reclaimed / not reclaimed Grant Companies

	2018 Start Up reclaimed Grant Companies	**2018 Start Up not reclaimed Grant Companies**
No. of Start Up reclaimed Grant Companies	216	705
Rate of Start Up not reclaimed Grant Companies	23,45%	76,55%

TIM Science Park: A Pioneer in Eastern Europe

TIM Science Park, the first scientific and technological park in Eastern Europe, plays a pivotal role in environmental protection and technology transfer in fields such as drying and heating technologies. Beyond fostering scientific, technological, and economic potential, the park actively facilitates collaboration between research institutions and businesses, ensuring practical applications of technological advancements (Popescu M., 2016).

The feasibility study and project planning steps from Table 1 were essential in structuring TIM Science Park's technology transfer framework, ensuring a clear roadmap for integrating research into industrial applications.

WESTTIM Innovation Cluster: Advancing Renewable Energy & Startups

The WESTTIM Innovation Cluster is a key entity in promoting environmental sustainability and renewable energy solutions. Benefiting from the PEDMEREMC project ("Performance and Excellence in the Field of Environment and Renewable Energy through Modern Cluster-Type Entities"), WESTTIM supports R&D efforts in intelligent specialization. Key partners, including Ioan Slavici University, TIM Science Park, and SC Titus SRL, contribute to its success.

This initiative fosters startup development within the renewable energy sector, facilitating cluster-based innovation inspired by TIM Science Park. Objectives include:

- Establishing a pilot cluster to optimize resource sustainability,
- Upgrading research laboratories in Timișoara,
- Conducting feasibility studies on underutilized renewable energy sources,
- Providing training on green skills,
- Supporting the creation of startups and spin-offs,
- Expanding businesses using R&D facilities, and
- Developing a new R&D infrastructure in Timișoara for continued innovation.

The grants, tax facilities, and business climate analysis components guided WESTTIM's strategy in securing funding and supporting startups, aligning with the PEDMEREMC project's objectives to foster R&D and innovation in renewable energy.

Cenei Technology Park & INO-MAT Startup: A Model for Technological Transfer

Cenei Industrial Park is home to several renewable energy companies, focusing on pellet and briquette production. The INO-MAT startup, established through the 2018 Start-Up Nation program, emerged within this park. The company specializes in sustainable materials for renewable energy and has leveraged technology transfer to improve industrial processes.

INO-MAT's collaboration with academia, including PhD-led research projects, resulted in the development of specialized software for calculating calorific values and ash content in biomass. This tool enhances production efficiency and demonstrates the practical application of technological transfer in renewable energy. The startup, supported by a 2019 Start-Up Nation contract, represents a successful example of how technology transfer entities facilitate innovation-driven entrepreneurship.

As modern technological entities have evolved, there are numerous companies, universities, and government organizations dedicating units for promoting technology transfer.

Figure 5. Pellet press – Pellet factory – INO-MAT project

Figure 6. Sample of straw pellets obtained with the pellet line

The project's results will help create conditions for sustainable development and enhance competitiveness by broadening the fields related to technology transfer, as illustrated in Figure 7, which highlights the key stages of the innovation process and technology transfer.

Fundamental research	Applied research Products, technologies and services Creating technology
Basic technology	Technological development Technological transfer Technology monitoring - fairs, magazines, the market
Activities	Activities from universities and research centers Activities of economic units Scans of activities - magazines, partnerships

Figure 7. The stages of innovation activity and technological transfer (Popescu M., 2001)

In conclusion, INO-MAT's dedication to transfer technology exemplifies its proactive approach towards driving innovation and progress in the industrial production of materials for renewable energy. Through effective knowledge transfer and collaboration, the company is well-positioned to make a meaningful impact on the renewable energy sector, advancing the development of sustainable solutions for a greener future.

The technological transfer, innovation process, and investment climate elements helped structure INO-MAT's approach in developing software for calorific value calculations, optimizing business operations within the renewable energy sector.

CONCLUSIONS

The role of technology transfer entities in fostering innovation and economic growth is evident in the case studies presented. The TIM Science Park, WESTTIM Innovation Cluster, and Cenei-based INO-MAT startup exemplify different yet complementary approaches to integrating research into real-world applications, particularly in the fields of renewable energy and sustainable materials.

One of the key contributions of technology transfer is its ability to bridge the gap between research institutions and industry, facilitating the development of new products and services. The INO-MAT startup, for example, leveraged academic research to create specialized software for calculating ash content and calorific values, benefiting both small-scale farmers and industrial pellet producers.

Additionally, the analysis of 921 startups under the "Start-Up 2018" funding program highlights the challenges and successes of early-stage enterprises. While 76.55% of companies remained operational, a significant 23.45% faced financial difficulties, leading to the recovery of non-repayable grants. This underscores the need for more robust support mechanisms for startups, particularly in high-tech and renewable energy sectors.

The findings also emphasize the importance of legislative frameworks in shaping the innovative landscape. Programs like PEDMEREMC and European funding initiatives play a crucial role in advancing technological transfer and startup development. Strengthening collaboration between universities, research centres, and businesses remains essential for fostering long-term innovation and economic competitiveness.

Ultimately, technology transfer centres and innovation clusters serve as catalysts for sustainable development, ensuring that scientific research translates into practical, market-ready solutions. By enhancing the ecosystem for startups and SMEs, they contribute significantly to the transition towards a more innovation-driven and environmentally conscious economy.

ACKNOWLEDGEMENTS

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50. ACTUAL TASKS ON AGRICULTURAL ENGINEERING

Original scientific paper

WORK OUTSIDE WORKING ENTITY IN AGRICULTURE – PERCEPTION ON OPPORTUNITIES AND RISKS

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ABSTRACT

Almost all applications in agriculture involve the use of remote sensing, GIS, decision-making, big data (collection and processing of farm data), IoT, etc. Intelligent systems create ethical issues and risks that should be assessed and proactively managed. At the same time, such systems permit and extend (totally and/or partially), the work outside the working entity (WOWE), in different shapes: teleworking, remote working, work from home, telecommuting, etc. (the concepts are not yet precisely defined). The paper examines the impact and challenges of the use of WOWE in agriculture in a few categories including fairness, transparency, accountability, sustainability, privacy, and robustness, based on perception analysis. A questionnaire for assessment of 8 factors considered important for WOWEs influence, realized in Google forms, was distributed in 57 micro, small and middle enterprises from agriculture, in west of Romania. Each factor was quoted based on the Likert scale (level 1 corresponding to indifferent and 5 to the most important). The answers were segmented on the employee's job, dimension of enterprise, age and studies. Information was statistically processed using Microsoft Excel and Stategraphics Centurion 19. Statistical significance and validity of hypothesis were verified by ANOVA and Multiple Range Tests. The most quoted as important factors were `Financial incentives from the enterprise` (38.6% of respondents quoted as level 4 (important)) and `Existence of appropriate work equipment and work protection` (quoted 34.1% of respondents at level 5(maximum importance)). The study can provide recommendations for conditions and risks by the use WOWE in farming (partial or integral).

Keywords: *work outside working entity, perception, factors, assessment*

INTRODUCTION

A strong transformation in business and organizations regarding the practices of work has been determined by the accelerated progression in ICT and technological advancements (Felstead and Henseke, 2017). Could be mentioned for agriculture a severe change in the work environment for many workers (HSE (Health and Safety Executive), 2021), especially generated by the use of unmanned aerial vehicles (UAV), (Anderegg et al., 2023; Goodrich et al., 2023), automation systems specific in agriculture (Babanatis et al., 2018), robotics and autonomous robots (Tucu et al., 2010; Yang et al., 2023), deep learning (Li et al., 2023), big data (Wu et al., 2023), machine learning (Goodrich et al., 2023); cloud computing, cybersecurity, etc. "Precision farming", also, uses a lot of sensors and robotic technologies in existing systems. However, such trends conflict with the low qualifications of employees in agriculture, their perception and motivation regarding occupational risks and specific management systems, especially in SMEs (Crisan et al., 2017; Tucu et al., 2019; Tucu A et al., 2021; Tucu A et al., 2023). Occupational health and safety (OHS) are also linked to the use of modern technologies (the protection of operators from impact, confusions and others (Pascuzzi and Santoro, 2017). In the same time, a significant development was registered in hardware, information technologies, smart systems, and software algorithms, which permitted equipment outside working entity health monitoring, fault diagnosis, and prognosis, enabling agriculture to improve equipment availability and to reduce operating costs throughout the system life-cycle (Manetto et al., 2017). One of the most important consequences is the possibility, also in agriculture, of working outside working entity, partially or fully working program. Working from home, remote working, teleworking, home office, and telecommuting became well-known forms of WOWE, main subjects of the discussions and analyses in research, due to the popularity of such jobs, conditions they offer, but, at the same time, they bring hidden new challenges (Karanikas and Cauchi, 2020). Permanent pressure is on the risks that WOWE could generate, particularly stress. For treating these risks, there is the possibility to transfer solutions and methods from other fields, which already were elaborated for evaluating and avoiding/reducing stress (Gusetoiu and Tucu, 2012; Gusetoiu and Tucu, 2013).

This paper aims to analyze the perception of several WOWE concepts and connected concepts, possible to appear in agricultural SMEs from the west side of Romania, identify gaps and associated solutions.

METHODS

The methodological flow, presented in figure 1, includes 5 principal steps. In the first step after a discussion (Brainstorming) with a group of 15 OHS specialists was established the questionnaire content. The first question referred to the job (position) and includes W-worker, M-manager and S-specialist. The second question asks about the enterprise`s dimension (microenterprises (< 9 employees) assigned MC, small (between 10-49 employees), assigned SM and middle (between 50-249 employees), assigned MD). The third question asks about age: A1- age under 25 years, A2- age between 25-40 years; A3- age between 40-60 years and A4- age over 60 years). The fourth question informs about qualification level: S1- for unqualified; S2- for secondary education; S3- for university studies; S4 – for master studies and S5- PhD.

The main question asks the respondent to evaluate and rank the selected factors, to determine the most important influences for WOWE activities in agriculture (motivational factors and risk factors). The used rating scale was based on 5 levels: 1 - indifferent factor (doesn't matter); 2- factor of low importance; 3- quite important factor; 4- important factor; 5- factor of maximum importance. The considered factors included three categories: - factor regarding state authority (A1- Controls from the state authority), factors related to the management department (M1-Financial incentives from the enterprise; M2-Controls and sanctions from the management of the enterprise; M3-Existence of appropriate work equipment and work protection), and worker-related factors (L1-Work stress; L2-The comfort of work activities in the family environment; L3-Social isolation; L4- Sedentarism, with risk, over time, of musculoskeletal conditions).

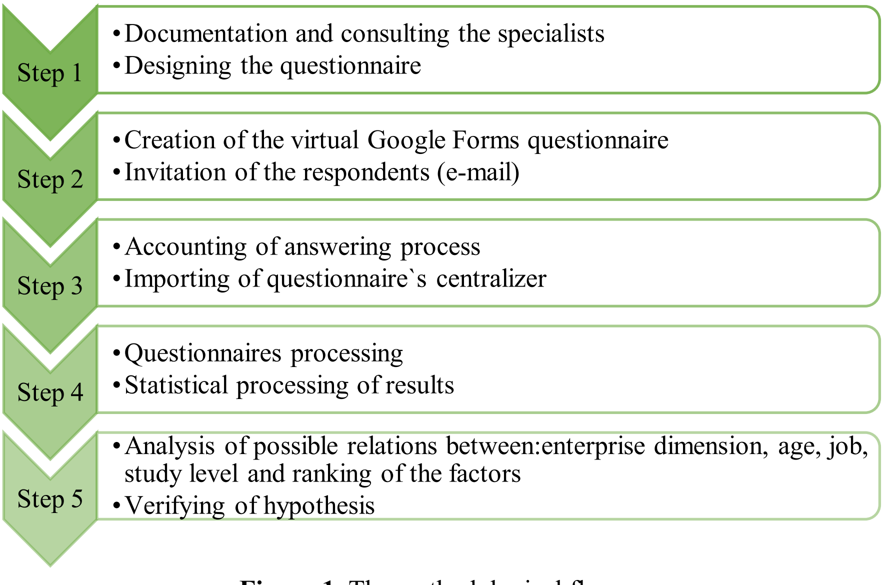


Figure 1. The methodological flow

After the questionnaires were collected, the results were prepared for statistical analysis using Microsoft Excel and STATGRAPHICS Centurion 19. The statistical relevance was verified Multiple-Sample Comparison by ANOVA, and Multiple Range Tests, if existing influences of enterprise dimension, field of activity, age and job/position on AI perception.

RESULTS AND DISCUSSION

88 employees from 58 enterprises answered the questionnaire. Figure 2 presents the repartition of respondents on enterprise dimension (MC, SM and MD). Similarly figure 3, 4 and 5 present the repartition respectively, on age (A1, A2, A3, A4), studies (S1, S2, S3, S4, S5) and position at work (W, S, M). Because the age of respondents was significatively distributed only in two groups (A2 and A3), in Table 1 the final statistic of centralized rates for factors (average level values rates for each factor), is presented structured only on

categories of respondents, grouped on enterprise dimension, study and position at work. The results of Multiple Sample Comparison for ANOVA test corresponding to enterprise dimension significance are presented in table 2.

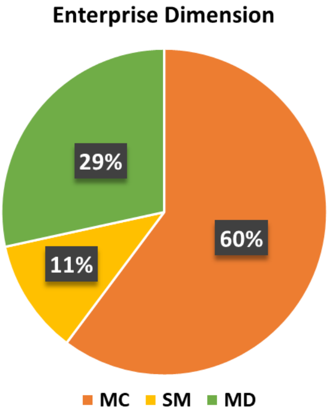


Figure 2. Structure of respondents based on Enterprise dimensions

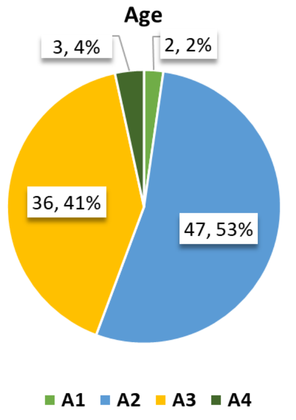


Figure 3. Structure of respondents based on Age

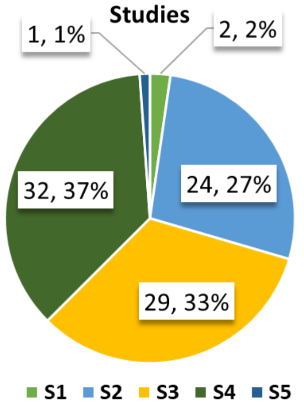


Figure 4. Structure of respondents, based on Studies

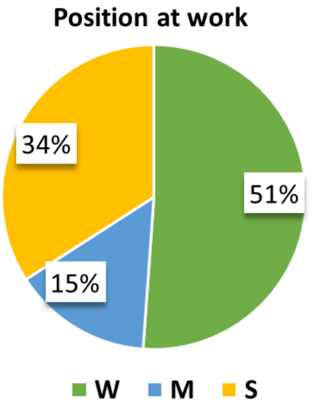


Figure 5. Structure of respondents based on Position at work

Since the P-value of the F-test is less than 0.05, there is a statistically significant difference between the rates given by group on enterprise dimensions at the 95.0% confidence level. So, it is statistically confirmed that enterprise dimension significatively influences the rate according to proposed factors. The differences between means of influence can be seen in figure 6a), Box-and-Whisker plot.

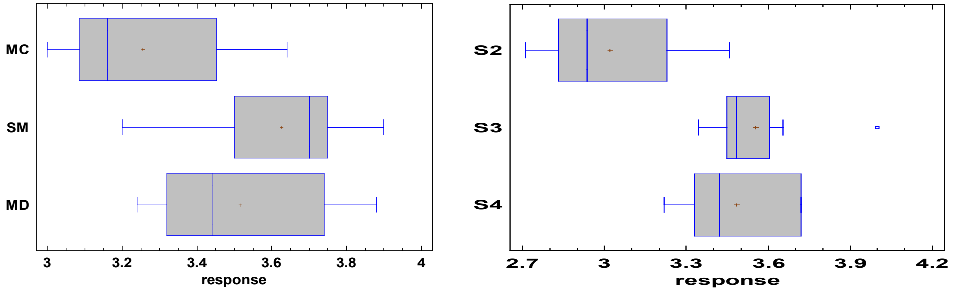
Table 1. The final statistic of centralized rates for factors

	Average of rate given for factor by respondents to:							
	A1	M1	M2	M3	L1	L2	L3	L4
TO	3.27	3.25	3.25	3.70	3.64	3.35	3.30	3.20
MC	3.00	3.06	3.11	3.64	3.51	3.40	3.15	3.17
SM	3.70	3.80	3.70	3.60	3.90	3.40	3.70	3.20
MD	3.68	3.44	3.36	3.88	3.80	3.24	3.44	3.28
S2	2.71	2.88	2.96	3.29	3.46	3.17	2.92	2.79
S3	3.34	3.45	3.48	4.00	3.66	3.55	3.48	3.45
S4	3.72	3.34	3.31	3.72	3.72	3.22	3.47	3.38
W	2.89	3.00	3.27	3.47	3.44	3.33	3.09	2.93
S	3.77	3.60	3.37	4.13	3.77	3.27	3.57	3.53
M	3.46	3.31	2.92	3.54	4.00	3.62	3.38	3.38

TO - Average of factor for all answers

Table 2. Results of ANOVA for Enterprise dimension`s influence

Source	Sum of Squares	Df	Mean Square	F-Ratio	P-Value
Between groups	0.578	2	0.289	5.33	0.0134
Within groups	1.139	21	0.054		
Total (Corr.)	1.718	23			



a) b)

Figure 6. Box-and-Whisker plot for Enterprise dimensions (a) and study (b)

The greatest rate of importance for factors came from small enterprises and the lowest from microenterprises (usually in MC not so many people can work outside work entity).

Similarly, table 3 and figure 6b) presents the results of Multiple Sample Comparison for ANOVA test corresponding to influence of study category and the differences between means of influence by Box-and-Whisker plot.

Table 3. Results of ANOVA for Study influence

Source	Sum of Squares	Df	Mean Square	F-Ratio	P-Value
Between groups	1.337	2	0.668	13.31	0.0002
Within groups	1.054	21	0.050		
Total (Corr.)	2.391	23			

The F-ratio, in this case, is equals 13.31and the P-value of the F-test is less than 0.05, so there is a statistically significant difference between the means of the 3 variables at the 95.0% confidence level. So, it statistically confirmed that study significatively influences the rate according to proposed factors. The greatest meaning was accorded from master degreed respondents.

Analysis of Multiple Sample Comparison results for ANOVA test (table 4) and Box-and-Whisker plot can conclude also position at work (W, S, M) significatively influence the accorded rate to the factors (F-ratio, in this case equals 5.62163 and the P-value of the F-test is less than 0.05), the greatest accorded meaning rate was from specialists.

Table 4. Results of ANOVA for position at work influence

Source	Sum of Squares	Df	Mean Square	F-Ratio	P-Value
Between groups	0.814	2	0.407	5.62	0.011
Within groups	1.52	21	0.072		
Total (Corr.)	2.333	23			

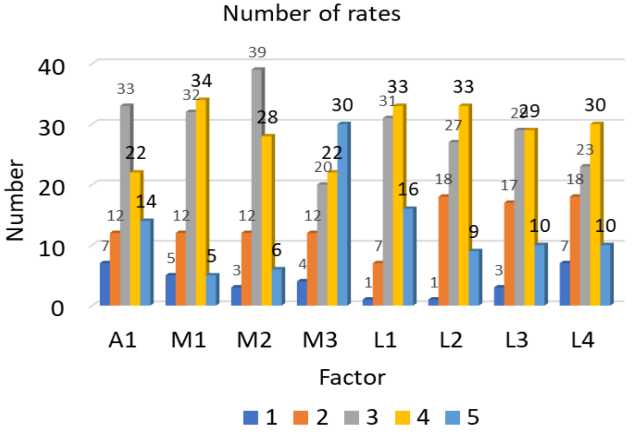


Figure 7. Total number of rates assigned to factors and levels

The repartition of level of importance assigned by respondents, cumulated on factors and level, presented in figure 7 indicates the most key factor `Existence of appropriate work equipment and work protection` (quoted 34.1% of respondents at rate 5 (of maximum importance)). Others key factors, less quoted, were: `Financial incentives from the enterprise` (38.6% of respondents quoted as level 4 (important)), `Work stress` and `The comfort of work activities in the family environment` (both quoted 37,5% of respondents at level 4 (important)). Such observation confirms the simultaneous generating of unwanted personal effects such as increasing stress caused by isolation, pressure from family and/or supervisors, till to conflicts, to carry out supplementary tasks (Song and Gao, 2020). The best results of such analysis can be obtained by individual approach and aggregation of the equilibrium between minimization of disadvantages and maximization of well-being working conditions at employer, family and enterprise level (Annarelli et al., 2020), also by new laws and reglemetations/regulations for reducing and/or compensate the absence of interacting between people (Darouei and Pluut, 2021).

CONCLUSIONS

WOWE in agriculture, despite a lot of advantages, recognized by employees, practiced for a long period can generate unwanted personal effects, almost increasing stress. Regulations/reglementations must be adopted to compensate for the absence of constant interacting during breaks and during tasks through formal and informal exchanges of information, meetings, and gatherings. drastically reduced outside work at the office.

Results of the present study confirm again that the importance of the WOWE approach in mitigating existing conflicts (aspirations vs. achievements, autonomy vs. control, and family vs. professional life etc.) becomes fundamental for minimizing disadvantages and maximizing well-being at the employer level, individual and/or family.

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50. ACTUAL TASKS ON AGRICULTURAL ENGINEERING

Original scientific paper

KEY PERFORMANCE INDICATORS IN OCCUPATIONAL HEALTH & SAFETY SYSTEMS IN AGRICULTURE

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ABSTRACT

Nowadays all activities in agriculture are confronted with many complex decisions regarding work conditions and work systems. Currently, various conditions of work, many hazards from complex equipment, competitions in technologies, efficiency, costs and prices, low qualification of employees and high speed of knowledge development, based on use software, AI, digitalization, etc. generate new challenges for OHS systems, especially in agriculture. Present paper proposes a hybrid method for compare the employee's perceptions regarding Key Performance Indicators (KPI), in different situations, typical for enterprises in agriculture, in Banat area (West of Romania). 35 agricultural enterprises from 3 fields of activities, typical in agriculture (15 enterprises from CAEN code 011-cereals cultivating, 10 enterprises CAEN code 012-fruit cultivation and 10 enterprises CAEN code 014 – livestock production), selected from different dimensions (microenterprises, small and middle), were the study object for a questionnaire (10 questions), regarding KPI perceptions distributed to 227 persons (19 in code 011, 84 in code 012 and 113 in code 014 and 11 persons in other activities). The results were proceeded by statistical analysis using Microsoft Excel and STATGRAPHICS. The relevance was verified by Multiple Range Tests and ANOVA was used for possible relations between education, seniority, age and field of activity and KPI perception. Conclusions and results can be used for OHS management systems optimization in different SMEs in agriculture, using the criteria of minimum cost and maximum safety, simultaneously with improvement of perception components of the work system *in agriculture, in conformity with EU regulations and state strategy for work environment.*

***Keywords**: occupational health and safety, risk management system, KPI, perception, optimization*

INTRODUCTION

The development of each country currently considers agricultural activities as one of the most important objectives, which requires agricultural mechanization, inevitable for the growth of agriculture (Huang et al., 2022). On the other hand, increasing of the number of agricultural machineries, in addition, determine supplementary costs and risks for work and safety (Mnerie et al., 2008; Tucu et al., 2010a; Crisan et al., 2017; Tucu et al., 2019), even the nonoperation scheduling cost gradually decreases, and both the nonoperation scheduling cost and the transfer distance decrease as the time window increases (He and Li, 2021). The most important consequences have become the generation of requirements regarding designing, implementation and improvement (not at all mandatory by law, also defined by specific standards (ISO, 2018)), of Occupational Health& Safety (OHS) management systems (MS) (Tucu A et al., 2021; Tucu A et al., 2023). For obtaining the best results it must be considered the workers as the most important resource of the enterprise, and, considering previous conditions so each employer must pay a special attention to OHS issues (Darabont et al., 2018). In fact, two dimensions of the OHS management systems are the most important: evaluation of workers' perception in conditions of impact of new technologies (Gusetoiu and Tucu, 2012; Gusetoiu and Tucu, 2013) and improvement of OHS management systems evaluation by using new tools specific to SMEs, especially in agriculture (Tucu et al., 2010b; Tremblay and Badri, 2018; Kazomir and Tucu, 2023). These dimensions must be related to implementation of emerging technologies in the agricultural production chain (Kukk et al., 2022). The effects of such new agricultural processes, based on the shift from traditional farming methods to intelligent and/or digital, have yet to be fully understood and generate new barriers (da Silveira and Amaral, 2023).

Based on International Labour Organisation (ILO) regulations and guides (ILO, 2022) and author's previous experience, including the frame of legal authority requirements, the paper proposes a hybrid model applicable for compare the employee's perceptions regarding Key Performance Indicators (KPI), in different situations, typical for small and middle enterprises (SMEs) in agriculture, in Banat area (West of Romania).

METHODS

Starting from the established objectives, the methodological flow is presented in figure 1 and includes 5 principal steps requesting: designing of the questionnaires (step 1), selection of enterprises and preparing the respondents (step 2), answering process (step 3), sorting and statistic processing of questionnaires (step 4) and interpretation of results (step 5). Designing of questionnaires include selection of 5 general questions by a brainstorming organized with 10 OHS specialists (were proposed questions regarding: age (code G for indicator, values: 1- age between 18-30 years; 2- age between 30-50 years; 3- age between 50-65 years and 4- age over 65 years); education (code E for indicator, values: 1- for unqualified; 2- for secondary education; 3- for university studies and 4 for postgraduate studies), seniority at the current company (code for indicator V, values: 1- for seniority less than 1 year; 2- for seniority between 1-3 years, 3- for seniority between 4-10 years and 4 for seniority more than 10 years), workplace of the activity related to the company (code P for indicator, values: 1- workplace inside the company; 2- for workplace at the customer, and 3- for workplace at home) and the gender). Also, into general section of the questionnaire were introduced question regarding enterprise (code formed from a letter specific to enterprise and a number for order of the questionnaire), and a code of worker activity (1- crop production; 2- horticulture (fruit cultivation); 3- livestock production; 4- food Industry or/and others). The 5 questions regarding KPI, were formulated according to the prescription of „Collecting data and measuring key performance indicators on occupational safety and health interventions- A Guidebook for implementer" (ILO, 2022).

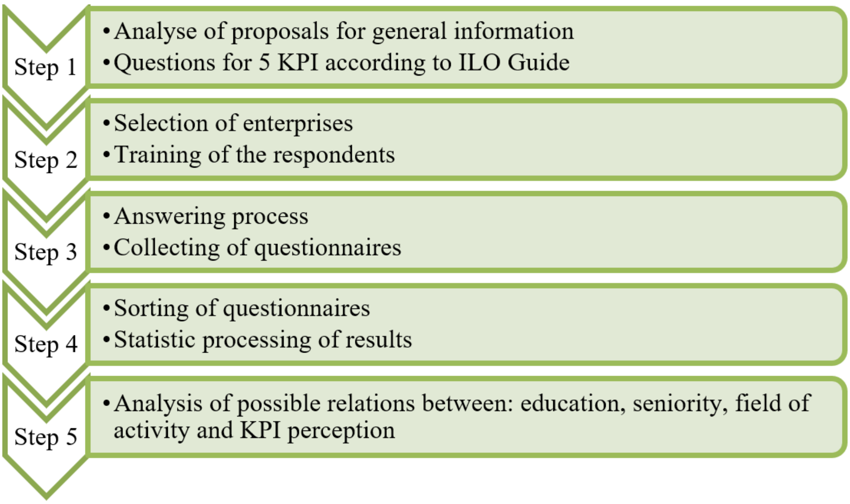

Figure 1. The methodological flow

Question for KPI I.1 (`How many times did you filled controlled? `), has assigned the value 0 for uncontrolled, value Y(yearly) for 1 to 3 controls per year, value T(quarterly) for 4 to 6 controls per year, value M (monthly) for 10 to 15 controls per year, value W(weekly) for 40 to 80 controls per year and value D (daily) for up to 150 controls per year. For the second question, I.2 (`Do you understand your rights and duties regarding OHS? `), the associated values were: 1 for answer yes, 2 for not and 3 for partially. For the third indicator, I.3 (`Did you receive any improvement actions regarding OHS? `), the associated values were: 1 for answer `yes` and 2 for `not`. For the fourth indicator, I.4 (`How many proposals and notices did you? `), the associated values were the number of declared proposals. The last questions, I.5 (`Do you considered satisfied regarding OHS to workplace? `), has associated values: 1 for answer yes and 2 for not. In the second step, 35 agricultural enterprises from 3 fields of activities, typical in agriculture of the west of Romania (15 enterprises from national code of activities classification (CAEN), code 011-crop production (noted 1), 10 enterprises from CAEN code 012-fruit cultivation (noted 2), and 10 enterprises from CAEN code 014 – livestock production (noted3)), selected from different dimensions (microenterprises (< 9 employees), small (between 10-49 employees) and middle (between 50-249 employees)), were selected for the questionnaires regarding KPI perceptions. If any person have another activity it was noted 4. The questionnaires were distributed to 227 persons (19 in code CAEN 011, 84 in code CAEN 012 and 113 in code CAEN 014, and 11 from other activities). The results were proceeded for statistical analysis using Microsoft Excel and STATGRAPHICS. The relevance was verified by Multiple Range Tests, and ANOVA, was used for possible relations between education, seniority, field of activity, age and KPI perception.

RESULTS AND DISCUSSION

The synthesis of results was processed by Microsoft Excel, mentioning the questionnaire code, Q (a group of letters, for enterprise, and order number). A section is presented in table 1.

Table 1. A section of processed answers

No.	Code A	Code, Q	Age V	Education E	Gender	Seniority S	WP, P	I.1	I.2	I.3	I.4	I.5
1	3	A1	2	3	1	3	1	Y	1	1	0	1
2	3	A2	1	2	1	3	1	Y	1	1	0	1
3	3	A3	2	2	2	2	1	Y	1	1	0	1
4	3	A4	3	3	1	3	1	T	1	1	0	1
5	3	A5	1	1	2	1	1	Y	1	1	0	1
6	3	A6	2	2	2	3	1	T	1	1	0	1
7	3	A7	1	3	1	3	1	Y	1	1	0	1
8	3	A8	2	1	2	3	1	Y	1	1	0	1
9	3	A9	2	2	1	2	1	T	1	1	0	1
10	3	A10	2	1	2	2	1	Y	1	1	0	1
11	3	A11	1	3	1	1	1	Y	1	1	0	1
12	3	A12	2	2	2	2	1	T	1	1	0	1
13	3	A13	1	3	2	3	1	Y	1	1	0	1
14	3	A14	1	2	1	3	1	Y	1	1	0	1
15	3	A15	2	1	1	3	1	T	1	1	0	1
16	3	A16	2	2	2	4	1	Y	1	1	0	1
17	3	A17	2	2	2	4	1	Y	1	1	0	1
18	3	B1	2	3	2	3	1	T	1	1	0	1
19	3	B2	3	2	1	4	1	T	1	1	0	1
20	3	B3	3	1	1	3	1	Y	1	1	0	1
21	3	B4	2	3	1	3	1	Y	1	1	0	1
22	3	C1	3	2	1	4	1	Y	1	1	0	1
23	3	C2	3	1	1	3	1	Y	1	1	0	1
24	3	C3	3	2	2	4	1	T	1		0	1
25	3	C4	3	2	2	4	1	T	1	1	0	1
26	3	D1	3	2	1	4	1	T	1	1	0	1
27	3	D2	3	3	1	4	1	T	1	1	0	1
28	3	E1	3	2	1	3	1	Y	1	1	0	1
29	3	E2	3	3	1	3	1	T	1	1	0	1
30	3	E3	3	3	1	3	1	T	1	1	0	1
…	…	…	…	…	…	…	…	…	…	…	…	…
227	3	AM1	2	3	2	3	1	Y	1	1	2	1

Because the received answers becomes from 99.11% workers from the workplace inside the enterprise, the influence of workplace was not interesting. In the same time, at questions regarding I.2, I.3, I.4 and I.5 the answers were, respectively, 93.39% for `YES I know the rights and obligations regarding OHS`, 94.71% have benefited from improvements in the field of OHS, 96.04% proposed less than 2 measures (80.18% have not any proposal, 15.86 have 1 or 2 proposals and only 3.96% have more than 3 proposals (inclusive)), and 96.47% declared are satisfied about OHS. As such, only the answer at the I.1 indicator were analyzed.

The weight of answers, pW, were calculated with next formula:

$$pW = 100 * \frac{ni}{227} \tag{1}$$

where ni - the number of answers at specific category (0 (no answer), D, W, M, T and Y).

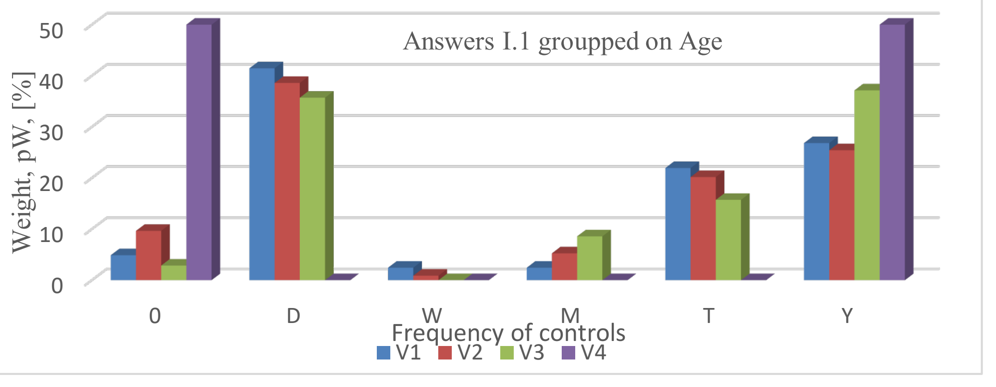

Figure 2. Value of answers for I.1, grouped on age

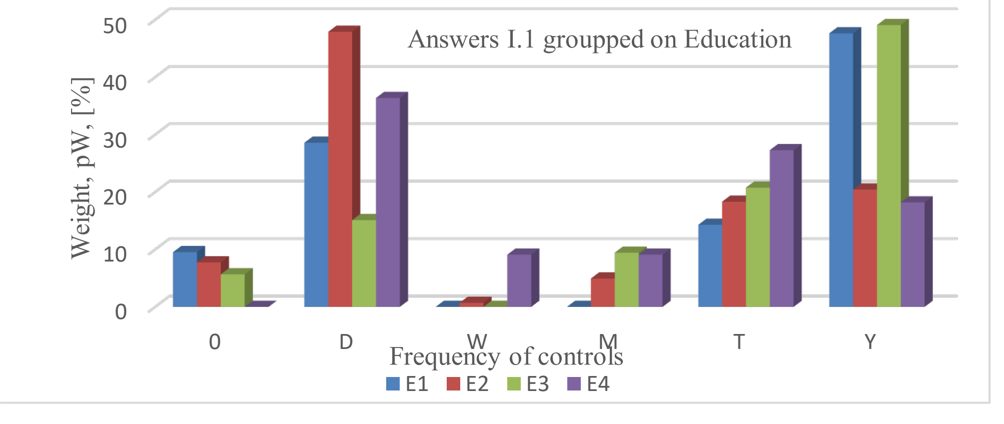

Figure 3. Value of answers for I.1, grouped on education

The values of extracted and calculated weights from table 1 for answer at I.1, segmented for 0 (no answer), D, W, M, T and Y are presented analyzed on next factors: age (figure 2), educations (figure 3), activity (figure 4) and seniority (figure 5).

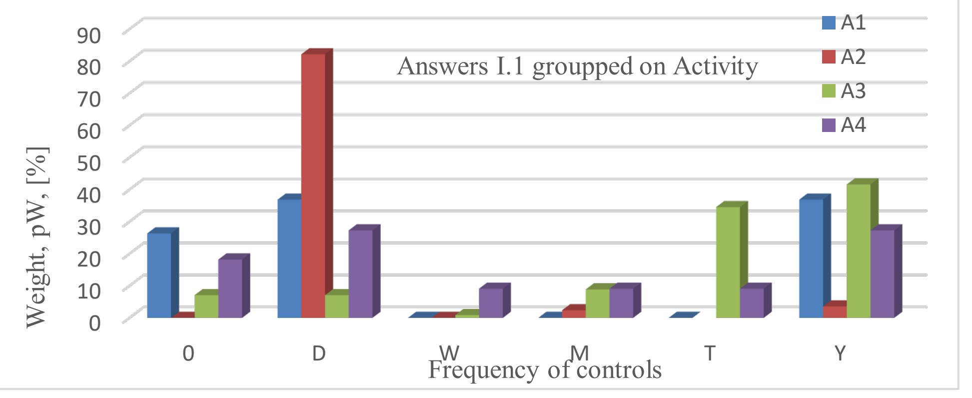

Figure 4. Value of answers for I.1, grouped on activity

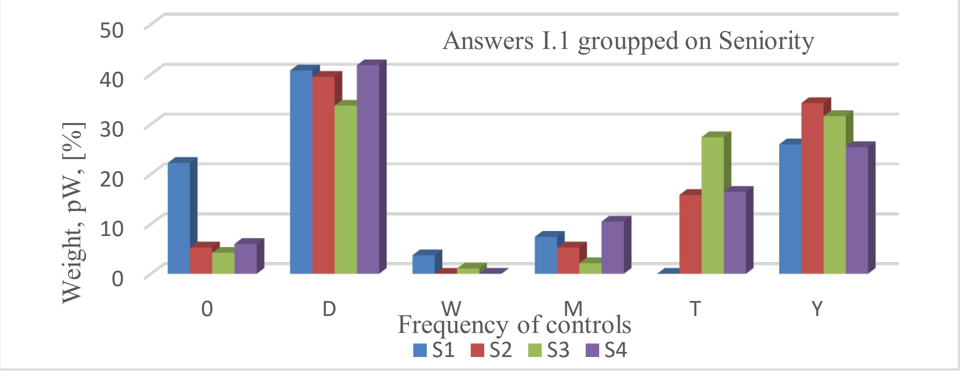

Figure 5. Value of answers for I.1, grouped on Seniority

The results of summary statistics analysis for the influence of factor education are presented in table 2 and the results of ANOVA test are presented in table 3.

Similarly, table 4 and table 5 present, respectively, the results of summary statistics analysis for the influence of factor seniority and the results of ANOVA test. Also, table 6 and 7 for field of activity and table 8 and 9 for age.

The ANOVA analysis demonstrated for all 4 factors analyzed that both component (a between-group component and a within-group component), has F-ratio estimated and P-value greater than or equal to 0.05, there is not a statistically significant difference between the means of the 4 variables at the 95.0% confidence level each factor.

Table 2. Summary Statistics analysis for the influence of factor education

	Count	Average	Standard deviation	Coeff. of variation	Minimum	Maximum	Range	Stnd. skewness	Stnd. kurtosis
E1	6	16.6667	18.5042	111.025%	0	47.619	47.619	1.02767	0.143634
E2	6	16.6667	17.1094	102.657%	0.704225	47.8873	47.1831	1.44326	1.12493
E3	6	16.6667	17.4328	104.597%	0	49.0566	49.0566	1.56875	1.40542
E4	6	16.6667	13.3815	80.2887%	0	36.3636	36.3636	0.418072	-0.429586
Total	24	16.6667	15.5906	93.5435%	0	49.0566	49.0566	1.92355	-0.0156266

Table 3. Results of ANOVA for Education

Source	Sum of Squares	Df	Mean Square	F-Ratio	P-Value
Between groups	0	3	0	0.00	1.0000
Within groups	4969.74	20	248.48		
Tot. (Corr.)	4969.74	23			

Table 4. Summary Statistics analysis for the influence of factor seniority

	Count	Average	Standard deviation	Coeff. of variation	Minimum	Maximum	Range	Stnd. skewness	Stnd. kurtosis
S1	6	16.6667	15.6698	94.0186%	0	40.7407	40.7407	0.570432	-0.472364
S2	6	16.6667	16.5322	99.1934%	0	39.4737	39.4737	0.641823	-0.893458
S3	6	16.6667	15.7321	94.3924%	1.05263	33.6842	32.6316	0.0495559	-1.55425
S4	6	16.6667	15.0862	90.5172%	0	41.791	41.791	0.910903	0.226095
Total	24	16.6667	14.6995	88.1971%	0	41.791	41.791	0.837793	-1.37416

Table 5. Results of ANOVA for Seniority

Source	Sum of Squares	Df	Mean Square	F-Ratio	P-Value
Between groups	17.7154	3	5.90514	0.01	0.9979
Within groups	9046.21	20	452.31		
Tot. (Corr.)	9063.92	23			

Table 6. Summary Statistics analysis for the influence of factor activity

	Count	Average	Standard deviation	Coeff. of variation	Minimum	Maximum	Range	Stnd. skewness	Stnd. kurtosis
A1	6	16.6667	18.6576	111.946%	0	36.8421	36.8421	0.15863	-1.47426
A2	6	14.6825	33.083	225.322%	0	82.1429	82.1429	2.43816	2.97812
A3	6	16.6667	16.9341	101.604%	0.884956	41.5929	40.708	0.926722	-0.698355
A4	6	16.6667	8.93811	53.6287%	9.09091	27.2727	18.1818	0.455939	-1.19501
Total	24	16.1706	19.8515	122.763%	0	82.1429	82.1429	3.57304	3.99302

Table 7. Results of ANOVA for activity

Source	Sum of Squares	Df	Mean Square	F-Ratio	P-Value
Between groups	17.7154	3	5.90514	0.01	0.9979
Within groups	9046.21	20	452.31		
Total (Corr.)	9063.92	23			

Table 8. Summary Statistics analysis for the influence of factor age

	Count	Average	Standard deviation	Coeff. of variation	Minimum	Maximum	Range	Stnd. skewness	Stnd. kurtosis
V1	6	16.6667	16.0618	96.3708%	2.43902	41.4634	39.0244	0.654915	-0.544018
V2	6	16.6667	14.1334	84.8006%	0.877193	38.5965	37.7193	0.584407	-0.328237
V3	6	16.6667	16.2296	97.3779%	0	37.1429	37.1429	0.540455	-0.979773
V4	6	16.6667	25.8199	154.919%	0	50.0	50.0	0.968246	-0.9375
Total	24	16.6667	17.3694	104.216%	0	50.0	50.0	1.40841	-0.945788

Table 9. Results of ANOVA for age

Source	Sum of Squares	Df	Mean Square	F-Ratio	P-Value
Between groups	2.72848E-12	3	0	0.00	1.0000
Within groups	6939.02	20	346.951		
Tot. (Corr.)	6939.02	23			

The same conclusion was after Multiple Range Tests each time (there are no statistically significant differences between any pair of means at the 95.0% confidence level, so all 4 factors are not significant influence on perception of OHS in agriculture). It can conclude 38.92% of workers perceive that they are controlled daily, 29.27% yearly, 14.89% quarterly, 6.3% monthly, 1,19% weekly and 9.41% perceive are not controlled relative OHS rules. Future research must analyze the influences of management (this research has not yet another term for comparison).

CONCLUSIONS

The use of KPI for determining the perception of OHS management systems in agriculture, as defined by ILO guide, could be useful to identify the most important problems and/or to optimize them. However, few particularities can vitiate the practical result, which makes it necessary to use statistical methods for analysis of the relevance of the results. It is possible that some apparently important factors do not have a significant influence or exercise it implicitly through other means, for example the management system of the agricultural enterprise.

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