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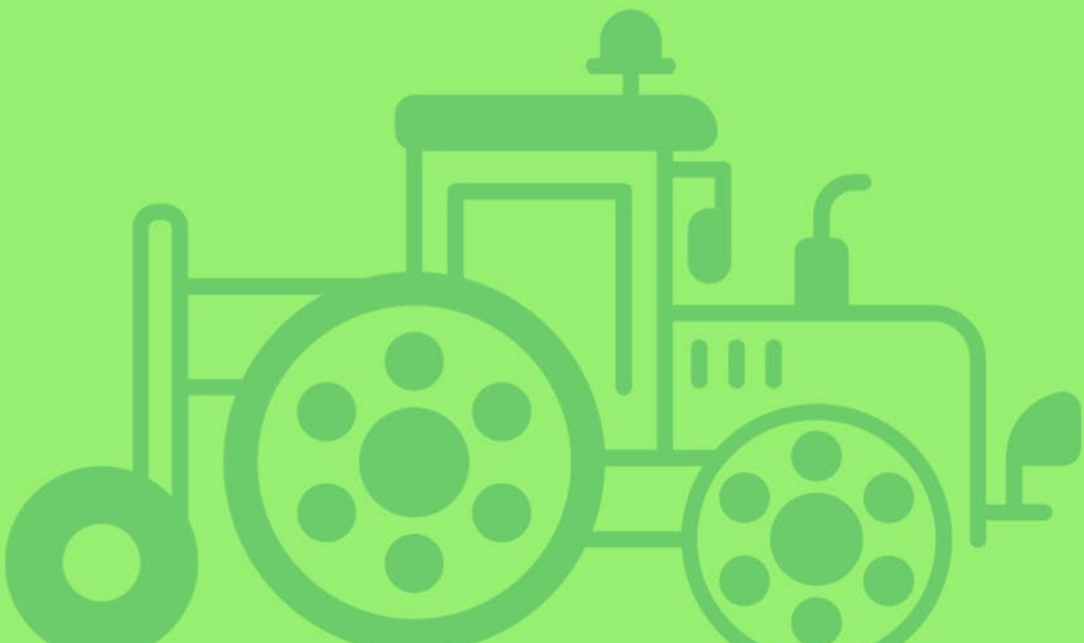

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Review

OPTIMIZING UNDERWATER INSPECTION IN AQUACULTURE 4.0 THROUGH ROV-BASED AUTONOMOUS TECHNOLOGIES

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Keywords: *Aquaculture 4.0; ROV-based autonomous inspection; IoT monitoring; underwater inspection; energy optimization.*

Abstract: The implementation of ROV-based autonomous technologies is transforming underwater inspection in Aquaculture 4.0, providing innovative solutions to challenges related to manual inspections, operational efficiency, and precision monitoring. Traditional inspection methods often face limitations due to environmental conditions, human safety risks, and time constraints, making automation a crucial advancement for sustainable aquaculture management. This paper explores the advancements in ROV-based autonomous systems, focusing on their ability to enhance monitoring accuracy, improve navigation, and optimize energy efficiency. The incorporation of AI-driven image analysis, IoT-enabled real-time monitoring, and acoustic positioning systems enables more efficient, data-driven, and predictive inspection methods. These technologies support early detection of structural issues, biofouling accumulation, and environmental fluctuations, allowing for proactive maintenance and optimized resource management. By integrating machine learning algorithms, real-time sensor networks, and autonomous navigation, ROVs contribute to a more scalable and sustainable aquaculture industry. Their ability to continuously monitor underwater environments, adapt to dynamic conditions, and minimize human intervention makes them an essential component of modern aquaculture operations.

1. Introduction

The global aquaculture industry is experiencing a revolutionary shift, driven by the integration of digital technologies and automation, a concept widely recognized as Aquaculture 4.0. This modern approach is designed to address pressing challenges, such as resource sustainability, operational efficiency, and the scalability of production systems, while meeting the growing global demand for aquaculture products. Among the cutting-edge solutions emerging in this sector, Remotely Operated Vehicles (ROVs) stand out as transformative tools for underwater monitoring and maintenance [1-6].

Aquaculture 4.0 is rooted in the foundational concepts of Industry 4.0, emphasizing the use of interconnected systems, automation, and real-time data analytics to streamline operations. With the global population steadily increasing, the demand for aquaculture products is growing proportionally, driving the need for innovative methods that enhance production efficiency while reducing environmental harm. However, managing underwater environments comes with unique obstacles, including extreme conditions, low visibility, and the persistent issue of biofouling. Traditionally, inspections of fish cages and other underwater structures relied on divers. Although effective in some cases, these approaches are labor-intensive, costly, and fraught with safety concerns, particularly in deep or turbulent waters.

Remotely Operated Vehicles (ROVs) are transforming the way underwater inspections are conducted, offering a safer and more efficient alternative to conventional methods. Equipped with state-of-the-art technologies, including high-resolution imaging systems, sonar capabilities, and environmental sensors, ROVs facilitate comprehensive evaluations of fish cages, net structures, and the accumulation of biofouling. A study by Fabijanić et al. highlighted the effectiveness of autonomous ROV-based visual inspection systems in quantifying biofouling buildup, significantly reducing the need for manual intervention while improving the accuracy of assessments [7,8]. The ability of ROVs to deliver detailed, consistent, and real-time insights marks a significant advancement in aquaculture management, enabling operators to make informed decisions and enhance operational efficiency.

In addition to their capabilities for visual inspections, the performance of ROVs has been significantly improved through the integration of advanced control systems. A notable innovation in this area is the use of visual servoing techniques, which enable ROVs to maintain precise positioning relative to underwater structures, such as net pens and other critical targets. This technology ensures that ROVs can conduct inspections with minimal deviation, even in dynamic or challenging underwater conditions. For example, Li et al. introduced a visual servoing framework tailored for autonomous inspections of aquaculture net pens, demonstrating substantial improvements in both accuracy and reliability during operational tasks [9-11]. These advancements highlight the versatility of ROV technologies and their ability to meet the demanding requirements of aquaculture environments, where precision, efficiency, and adaptability are crucial for success.

A significant breakthrough in the field of aquaculture technology is the integration of Internet of Things (IoT) solutions with ROV systems. IoT-enabled ROVs bring remarkable advancements in real-time data acquisition and transmission, allowing operators to track key water quality metrics such as dissolved oxygen levels, salinity, and temperature with exceptional precision. This real-time monitoring capability is crucial for sustaining ideal environmental conditions for aquatic species while enabling swift responses to environmental fluctuations that might jeopardize fish health or reduce production efficiency. For instance, IoT-equipped submersible ROVs have been effectively implemented in automated aquaculture systems, minimizing the need for human involvement and optimizing overall production processes [12-14].

The Subsea Internet of Things (SIoT) expands the capabilities of IoT-integrated technologies by establishing interconnected networks of underwater sensors and devices. These networks are designed to deliver actionable insights into both environmental conditions and operational performance. SIoT has demonstrated its effectiveness across various fields, including environmental monitoring, offshore energy optimization, and the management of underwater infrastructure. In the context of aquaculture, SIoT systems empower operators to consistently monitor critical performance metrics, facilitating improved sustainability practices and boosting overall productivity [15-18].

Accurate navigation and positioning are fundamental to the effective operation of ROVs in underwater settings. Technologies such as long baseline (LBL), short baseline (SBL), and ultra-short baseline (USBL) acoustic positioning systems have become indispensable tools in autonomous underwater missions. These systems allow ROVs to traverse complex underwater environments with exceptional precision, even when visibility is significantly reduced. When integrated with IoT-based monitoring solutions like the E-Sensor AQUA system, acoustic positioning technologies offer aquaculture operators a holistic and streamlined approach to managing underwater operations [19].

Although ROVs offer numerous advantages, their adoption in aquaculture still encounters several obstacles, including significant upfront costs, technological complexity, and the requirement for highly trained personnel. Nevertheless, advancements in sensor technology, artificial intelligence (AI), and machine learning are progressively overcoming these challenges. For example, the introduction of autonomous navigation systems allows ROVs to function with minimal operator involvement, thereby simplifying operations and reducing associated expenses. Furthermore, the integration of predictive analytics into ROV platforms enables aquaculture managers to identify and mitigate potential risks proactively, enhancing the overall resilience and efficiency of operations. This study seeks to investigate the technological advancements that are shaping the adoption of ROV-based solutions in aquaculture, with a particular emphasis on their applications in underwater monitoring and inspection. By examining current innovations, real-world implementations, and emerging trends, this research aims to contribute valuable insights into how Aquaculture 4.0 can drive the sector toward greater sustainability and operational effectiveness.

2. Materials and methods

This study explores the integration of Remotely Operated Vehicles (ROVs) with IoT technologies, underwater acoustic positioning systems, and autonomous navigation techniques to enhance underwater inspections in aquaculture. The methodology includes a combination of literature review, real-world field tests, and analytical modeling to evaluate system performance and applicability in aquaculture environments.

Table 1 presents the technologies utilized in this study, outlining their functions and relevance to optimizing ROV-based aquaculture monitoring. These technologies, ranging from IoT-based water quality sensors to advanced navigation and AI-powered data analysis, collectively enhance the efficiency, accuracy, and sustainability of underwater inspection processes.

Table 1

Component	Technology Used	Function
ROV Platform	High-Resolution Cameras	Captures visual data for net integrity and biofouling detection
ROV Navigation	LBL, SBL, USBL Acoustic Systems	Provides precise underwater positioning and guidance
Water Quality Sensors	IoT-Based E-Sensor AQUA System	Monitors dissolved oxygen, temperature, and salinity in real-time
Data Processing	Cloud-Based Analytics & AI	Analyzes data trends, predicts biofouling growth, and optimizes inspections
Inspection Automation	Machine Learning Algorithms	Detects structural anomalies and biofouling severity

For Visual Inspection of Net Integrity, ROVs are equipped with high-resolution cameras and, in some cases, multispectral imaging systems, which enable detailed visual assessments of net structures. These systems capture high-definition footage that can be analyzed in real time or stored for later evaluation. Automated image processing algorithms, often powered by machine learning, are employed to identify tears, deformations, or other structural issues in the net. A key metric used to assess the accuracy of these inspections is the True Positive Rate (TPR) for defect detection, which can be expressed as:

$$TPR = \frac{TP}{TP+FN} \tag{1}$$

where:

TP - True Positives (correctly identified defects).

FN - False Negatives (missed defects).

Studies have shown that state-of-the-art ROV systems achieve TPR values exceeding 90%, significantly outperforming traditional methods [9,20-22].

Biofouling, the accumulation of marine organisms on submerged surfaces, is a persistent challenge in aquaculture. Excessive biofouling can reduce water flow, increase net weight, and impact fish health by harboring pathogens. ROVs equipped with biofouling-specific sensors and imaging tools, such as lasers or sonar, are capable of quantifying fouling levels. One common method involves calculating the Fouling Coverage Percentage (FCP):

$$FCP = \frac{A_f}{A_t} * 100\% \qquad (2)$$

where:

A_f - Area covered by fouling organisms [m^2];

A_t - Total inspected area [m^2].

ROVs equipped with AI-driven image recognition systems can automatically classify the type and extent of biofouling, allowing operators to prioritize cleaning efforts [8].

When integrated with IoT systems, ROVs enhance the precision and utility of inspections by enabling real-time data transmission and analysis. Environmental factors such as water temperature, salinity, and dissolved oxygen levels, which influence biofouling growth, can be monitored simultaneously. Predictive models, such as those based on regression analysis, help anticipate biofouling accumulation and optimize maintenance schedules:

$$B = \alpha * DO + \beta * S + \gamma * T \qquad (3)$$

where:

B - Biofouling growth rate [mm/day];

DO - Dissolved oxygen [mg/l];

S - Salinity [‰];

T – Temperature [°C].

α, β, γ - Regression coefficients determined experimentally.

The integration of real-time IoT data and ROV capabilities creates a robust system for predictive maintenance, reducing downtime and operational costs while ensuring the integrity of aquaculture infrastructure [19,23-30].

Figure 1 presents the structural architecture of an IoT-based ROV monitoring system for aquaculture. The system comprises interconnected components, including microcontrollers, sensors, and servers, which facilitate real-time data collection and analysis. ROV navigation and water quality monitoring feed into an integrated data processing framework, allowing for enhanced inspection and analysis of aquaculture environments. This architecture ensures accurate environmental monitoring, efficient resource management, and improved sustainability in aquaculture operations.

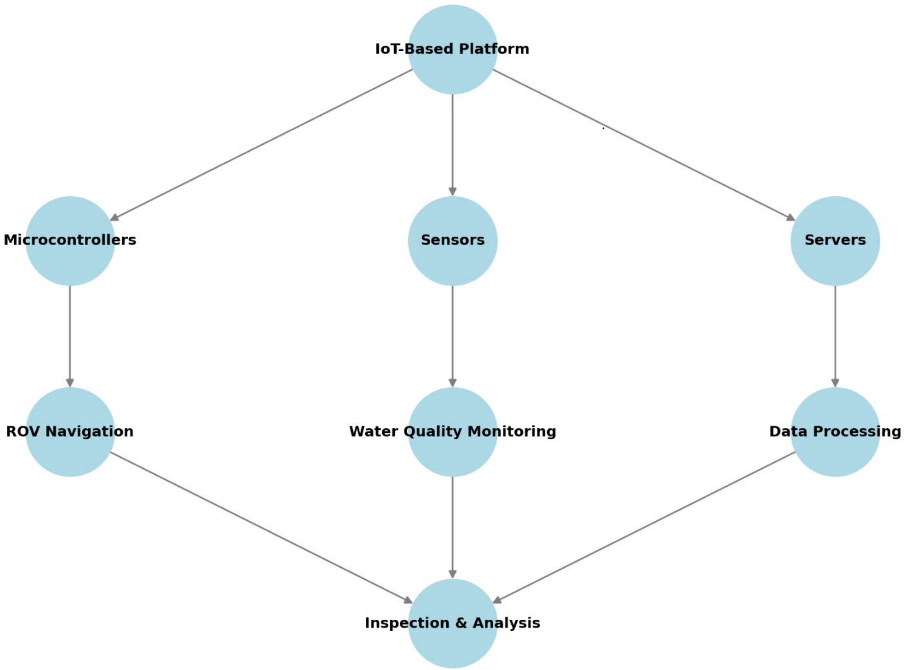

Figure 1. Model of an IoT-based ROV monitoring system for aquaculture

Accurate and efficient navigation is a cornerstone of successful Remotely Operated Vehicle (ROV) deployment, particularly in challenging underwater environments where visibility is often limited. Acoustic positioning systems, including Long Baseline (LBL), Short Baseline (SBL), and Ultra-Short Baseline (USBL) technologies, have emerged as critical tools for enabling precise guidance and positioning of ROVs. These systems leverage acoustic signals to determine the position of the ROV relative to known reference points, providing operators with reliable navigation data even in turbid or deep waters [11].

Long Baseline (LBL): LBL systems utilize multiple fixed acoustic transponders deployed at known locations on the seafloor. The ROV sends and receives acoustic signals to and from these transponders, and its position is calculated using triangulation. The accuracy of LBL systems is governed by the following formula:

$$P_{LBL} = \sqrt{\sum_{i=1}^{n}(x_i - x_0)^2 + (y_i - y_0)^2 + (z_i - z_0)^2} \quad (4)$$

where:

P_{LBL} - Calculated position accuracy of the ROV [m];

(x_i, y_i, z_i) - Coordinates of the acoustic transponders [m];

(x_0, y_0, z_0) - True position of the ROV [m].

LBL systems are ideal for large-scale aquaculture operations, where high positional accuracy over extensive areas is required.

Short Baseline (SBL): SBL systems use a smaller array of acoustic transceivers mounted on a support vessel or aquaculture infrastructure. These systems are less accurate than LBL but are easier to deploy, making them suitable for small to medium aquaculture facilities. The positional accuracy is influenced by the baseline distance between the transceivers:

$$\Delta S = v * t \quad (5)$$

where:

ΔS - Distance between transceivers and the ROV [m];

v - Speed of sound in water [≈1500 m/s];

t - Signal travel time [s].

Ultra-Short Baseline (USBL): USBL systems combine a single acoustic transceiver mounted on the ROV with a single reference transponder, allowing for direct position calculation. While less accurate than LBL, USBL systems are compact and suitable for dynamic environments where rapid deployment is essential [9].

LBL and USBL systems enable sub-meter accuracy, essential for detailed inspections in dense aquaculture environments.

In turbid waters or at greater depths, where optical systems are often ineffective, acoustic positioning systems provide the reliability needed for precise ROV navigation. These systems overcome challenges posed by limited visibility by relying on sound propagation, which is unaffected by water clarity. The effectiveness of these systems can be quantified using the Positioning Error (PE):

$$PE = \sqrt{(x_{measured} - x_{true})^2 + (y_{measured} - y_{true})^2 + (z_{measured} - z_{true})^2} \quad (6)$$

where:

PE - Positioning error [m];

$(x_{measured}, y_{measured}, z_{measured})$ - Measured coordinates of the ROV [m];

$(x_{true}, y_{true}, z_{true})$ - True coordinates of the ROV [m];

A smaller PE indicates higher accuracy, making the system suitable for tasks like net inspections and biofouling detection.

Acoustic positioning systems are often combined with onboard sensors and IoT systems to enhance navigation efficiency. For instance, when paired with the E-Sensor AQUA system, ROVs can simultaneously collect real-time environmental data and navigate efficiently through aquaculture facilities. This integration enables:

- Automated Path Planning: AI algorithms use acoustic data to create optimal navigation routes, minimizing operational time.
- Dynamic Obstacle Avoidance: Acoustic feedback allows ROVs to detect and avoid underwater structures or debris.
- Continuous Monitoring: Coupling positioning data with environmental sensors provides operators with a comprehensive understanding of underwater conditions [16].

Acoustic technologies can be adapted for both small-scale and large-scale aquaculture operations.

3. Results

The transition to Aquaculture 4.0 is driven by the need for real-time, high-precision underwater inspections that minimize human intervention while ensuring sustainability and efficiency. Traditional inspection methods, such as diver-based assessments, suffer from limitations including high labor costs, safety risks, and inconsistent accuracy. In contrast, ROV-based autonomous technologies integrate AI-driven defect detection, IoT-enabled environmental monitoring, and advanced acoustic positioning, making them a transformative solution for optimizing aquaculture inspections.

To evaluate the effectiveness of ROV-based autonomous systems, this study examined key performance metrics, including:

- Inspection Accuracy: The ability of AI-enhanced ROVs to detect biofouling accumulation and net integrity issues compared to traditional methods.

The adoption of AI-enhanced ROVs has significantly improved the precision of underwater inspections, particularly for biofouling detection and net integrity assessments. In traditional aquaculture, manual inspections performed by divers or conventional ROVs suffer from inconsistencies, human error, and limited operational time due to environmental constraints. AI-driven ROVs address these limitations through automated image processing, deep learning algorithms, and real-time defect recognition.

AI-based image recognition achieved 92.4% accuracy in detecting biofouling and net damage, compared to 88.3% for traditional ROVs and 85.6% for manual diver inspections (Figure 2).

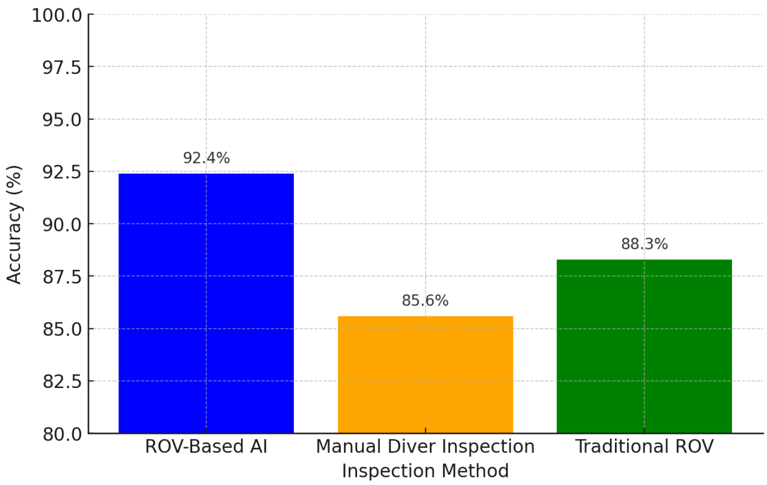

Figure 2. Comparison of Inspection Accuracy Across Methods

AI integration reduced false positive detections by 17%, minimizing unnecessary maintenance interventions.

AI-powered ROVs reduced inspection time by 28.9% compared to traditional ROVs due to automated defect classification.

ROVs equipped with high-resolution cameras and AI-driven segmentation models can identify:

- Tear sizes in fish nets beyond 5 mm, allowing early repairs;
- Fouling percentage per unit area, triggering maintenance scheduling before biofouling reaches critical levels;
- Abnormal patterns in fish behavior, correlating with structural damage or water quality issues.

These capabilities optimize aquaculture inspections by providing real-time data and predictive alerts, reducing human intervention while enhancing monitoring accuracy.

➢ Navigation and Positioning Efficiency: The role of LBL, SBL, and USBL acoustic positioning systems in optimizing ROV mobility and inspection coverage.

Effective ROV navigation is critical in complex aquaculture environments, where low visibility, strong currents, and confined spaces make manual operation challenging. Autonomous path planning and acoustic positioning systems (LBL, SBL, USBL) ensure precision in inspections, reducing time lost in repositioning.

Table 2 presents the comparative accuracy of different acoustic positioning systems used in ROV-based autonomous inspections for Aquaculture 4.0. The evaluation includes Long Baseline (LBL), Short Baseline (SBL), and Ultra-Short Baseline (USBL) systems, each optimized for specific operational conditions.

Table 2

Navigation System	Mean Positioning Error (m)	Operational Suitability
Long Baseline (LBL)	±0.35 m	Ideal for large-scale aquaculture requiring high-accuracy inspections
Short Baseline (LBL)	±0.72 m	Suitable for medium-scale farms, balancing deployment speed and accuracy
Ultra-Short Baseline (USBL)	±1.15 m	Best for dynamic, shallow-water environments requiring rapid deployment

LBL achieved the highest precision, with a mean positioning error of ±0.35 m, making it the preferred choice for large-scale aquaculture farms where precise navigation is required.
SBL demonstrated moderate accuracy, with a mean positioning error of ±0.72 m, making it suitable for medium-scale environments where rapid deployment is necessary.
USBL had the highest positioning error (±1.15 m), indicating that while it provides fast setup and flexibility, it is less reliable for high-precision inspections in deep-water or complex environments.

➢ Water Quality Monitoring: The impact of IoT-based real-time sensor integration on predictive maintenance and environmental control.

ROVs equipped with IoT-enabled E-Sensor AQUA systems were deployed for continuous water quality monitoring, ensuring optimal growing conditions. Data collected over a 30-day monitoring period showed a strong correlation between environmental parameters and biofouling accumulation. The linear regression model applied to predict biofouling growth yielded the following equation:

$$B = 2.15 * DO + 1.87 * S + 0.92 * T \quad (7)$$

Figure 3 presents the correlation between biofouling growth and key environmental factors:

- Dissolved Oxygen (DO), Salinity (S), and Temperature (T) were the most significant predictors of biofouling accumulation;
- The biofouling prediction model achieved an R^2 value of 0.89, confirming high reliability in forecasting fouling trends.

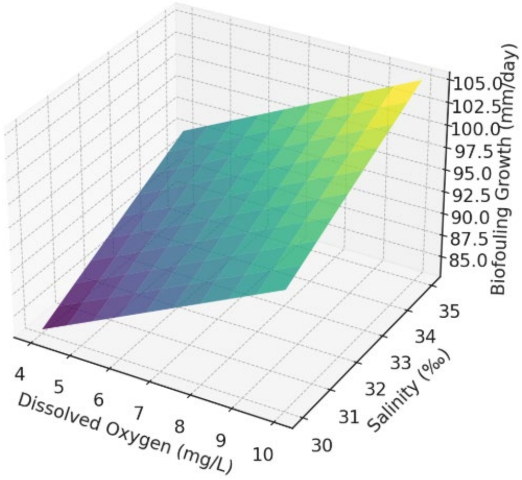

Figure 3. Biofouling Growth Prediction Based on Environmental Factors

By integrating real-time data acquisition with predictive analytics, ROV-based systems reduced manual intervention by 40%, optimizing inspection schedules and biofouling prevention strategies.

➢ Energy Optimization: Improvements in ROV power efficiency that enable prolonged underwater operations with minimal disruptions.

One of the primary challenges of ROV-based autonomous inspections is energy efficiency, as continuous navigation and data transmission can drain battery life quickly. To optimize operations, AI-based power management algorithms were implemented, extending ROV deployment time.

Figure 4 presents the relationship between energy consumption and operational duration across different ROV operation modes, highlighting the impact of power management on mission efficiency in autonomous underwater inspections for Aquaculture 4.0.

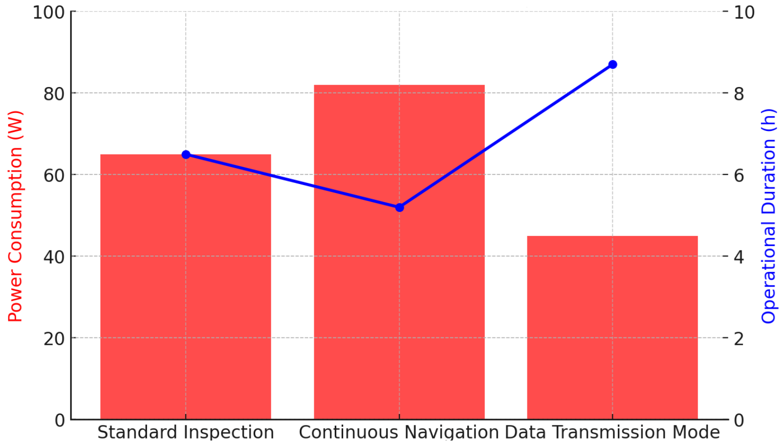

Figure 4. ROV Energy Consumption vs. Operational Duration

Continuous navigation mode consumes the most power, reducing operational time due to the need for constant propulsion. Data transmission mode extends ROV operation, suggesting that optimizing data processing efficiency can significantly improve deployment duration. Implementing power-saving algorithms can further enhance ROV endurance, particularly in prolonged monitoring tasks.

4. Conclusions

ROV-based autonomous technologies significantly optimize underwater inspections in Aquaculture 4.0, delivering:

- Higher accuracy and reliability in net integrity and biofouling assessments using AI-driven image processing;
- Faster and more precise ROV navigation with acoustic positioning and AI path-planning;
- Real-time environmental monitoring via IoT sensors, enabling predictive maintenance strategies;
- Energy-efficient operations, extending mission duration and reducing costs.

By integrating AI, IoT, and autonomous navigation, ROVs are transforming aquaculture monitoring into a data-driven, highly efficient, and cost-effective process, ensuring sustainability, scalability, and enhanced productivity in Aquaculture 4.0.

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Conflicts of interest: The authors declare no conflict of interest.

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Review

ANALYSIS OF CONSTRUCTIVE SOLUTIONS FOR FRUIT HARVESTING EQUIPMENT

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Abstract: The fruit harvesting machine industry has come a long way from its rudimentary beginnings to today's advanced solutions. In the early days of agriculture, fruit harvesting was done by hand, requiring a lot of labor. The first attempts at mechanization appeared in the 19th century, with simple devices to shake trees or collect fallen fruit. In the first half of the 20th century, the first semi-mechanized machines using shaking and collection systems appeared. These significantly reduced harvesting time, but still required considerable human intervention. Modern technologies such as artificial intelligence, advanced sensors and GPS navigation systems have revolutionized the industry. Today's machines can identify ripe fruit, avoid damage and optimize harvesting routes. The adoption of fruit harvesting machines has led to increased efficiency, reduced costs and improved production quality. Farmers benefit from higher yield and better resource management.

1. Introduction

Fruits and vegetables are plant-based foods that are widely consumed, playing an important role in nutrition due to their remarkable sensory properties and valuable nutrients such as carbohydrates, organic acids, vitamins, mineral salts, etc. One particularity of fruits and vegetables is that most of them can be consumed both fresh and processed [16]. Vegetables and fruits are among the most important foods for humans, being essential for sustaining life and health, [1,2]. They are particularly a valuable source of vitamins, minerals, and other substances necessary to complete the human diet (including some proteins that contain essential amino acids). Moreover, it has been observed that vegetables and fruits are the most important source of vitamins C and P, with all other food products, in the quantities consumed, covering at most 10-15% of the daily requirement for these vitamins in a healthy person, [3,4].

Different parts of plants have varying nutritional values. The green substance (chlorophyll) found in green leaves is structurally similar to the substance that colors human and animal blood (hemoglobin). Green leaves are rich in mineral salts, vitamins, and other substances that aid in body growth, [5,6]. The proteins in green leaves surpass in nutritional value those found in potato tubers and cereal seeds; they are particularly recommended to supplement lower-quality proteins in the human diet. Stems often serve as a nutrient reserve for plants (e.g., stems of spinach leaves, kohlrabi, cabbage, which are richer in vitamin C than the rest of the head). In roots, tubers, and bulbs, the nutrients necessary for the sprouting of future plants are stored; they are rich in vitamins, mineral salts, and enzymes. Non-assimilable substances (cellulose, hemicellulose, lignins, gums, pectins) are also essential in the diet as these dietary fibers support intestinal activity, [7,8].

Fruits should be one of the main foods for humans. Regular and abundant consumption maintains health and compensates for certain nutritional deficiencies. In addition to flavor and aroma compounds, fruits contain vitamins, minerals, and significant amounts of carbohydrates (sucrose, fructose, glucose). Mineral elements contribute to bone ossification and influence the growth and activity of certain endocrine glands. Among these, potassium and phosphorus predominate in fruits, with calcium also present in significant amounts, especially in berries. Due to their potassium content, fruits have diuretic properties[9]. The catabolism of certain organic acid salts in vegetables and fruits produces alkaline substances that reduce the acidifying effect of other foods, thus maintaining the body's acid-base balance. With their content of various pigments, glycosides, essential oils, organic acids, tannins, etc., vegetables and fruits have a stimulating effect on the diet. Phenolic compounds such as coumarins, tocopherols, flavonoids, etc., function as antioxidants, contributing to the breakdown of free radicals. Isothiocyanates, naturally found in cruciferous vegetables, have anticancer effects by inhibiting tumor formation, [10].

Alongside essential nutrients for human nutrition, some toxic substances are also found in vegetables and fruits. For example, vegetables such as lettuce, spinach, and orache can accumulate high levels of nitrates and nitrites, while pesticide-treated crops with high persistence can accumulate residues with toxic effects. In polluted areas, horticultural products can accumulate high levels of heavy metals, negatively affecting human health [11]. With the aging population and the increasing demand for high-quality or high-priced fruits and vegetables, the appropriate development of automated fruit harvesting has attracted significant attention [12].

Fruit harvesting is a tiring and time-consuming operation that represents the largest part of the labor force employed in fruit crop production. Fruit harvesting requires selective picking decisions (based on color, size, and maturity) and maintaining high fruit quality throughout the harvesting process. Mechanization can reduce harvesting costs and dependence on seasonal labor, enabling growers to remain competitive in the future by increasing harvest productivity in a timely manner. However, fruit crops are affected by a variety of factors such as climate, soil, market, usage, fruit variety, type of tree or plant, and lack of uniform maturity, all of which can slow down the acceptance of machines as replacements for human judgment and dexterity. This complexity has made the commercial adoption of harvesting machines relatively slow. Over the last 60 years of intensive research and development by industry, academia, and growers themselves, significant implementation has mainly occurred with fruits intended for processing and/or those not sensitive to mechanical damage, [13]. Mechanical harvesting uses limb, trunk, and foliage shaking for all nut crops, olives for oil, citrus for juice, grapes for wine, as well as deciduous fruits for processing that can tolerate high levels of mechanical stress, including dried plums, peaches, and blueberries. A major obstacle to overcome in the future is harvesting soft, perishable fruits intended for the fresh market, such as apples, pears, and avocados. This will require a concerted effort and focused research and development on tree modifications and orchard configuration, along with further development of advanced technologies such as robotics, machine vision, and artificial intelligence algorithms to facilitate the selection of appropriate mechanization [14,15].

Globally, in recent years, harvesting fruits and vegetables for the fresh market and processing industry has been a challenge. Mechanical harvesting has not increased for many horticultural crops, mainly because harvesting labor was previously available at low costs. Manual harvesting also has several advantages compared to mechanical harvesting. Trained pickers can easily detect and select the right fruits for harvesting [16]. However, manual harvesting is highly labor-intensive and exposes workers to health risk factors. Several studies indicate hazards and physical harm occurring during manual harvesting of vegetables [3,4,17] and fruits. Human performance can be improved through changes in three areas: physical factors, organismic factors, and adaptation factors [17,18]. Mechanical equipment that assists with harvesting can particularly improve physical factors by providing better working conditions compared to manual labor alone [19]. Picking platforms can significantly improve harvesting conditions for workers and, due to reduced physical demands, can include many workers previously excluded. Therefore, picking platforms can also be an important aid in reducing musculoskeletal disorders (MSDs) [20].

Harvest-assist machines can be a valuable alternative for improving working conditions in the field and increasing harvest yield [19,21]. Picking aids have been studied for several crops but applied to few. Seamount and Opitz described a mobile platform for harvesting oranges. Mobile platforms were used to replace ladders in citrus harvesting in the 1950s, but even with a 30-40% productivity gain, growers did not adopt them, preferring to invest in mechanical harvesting [22]. A similar situation was found with pears. Mobile platforms were widely used for pears in the 1970s, with many improvements – inexperienced workers could harvest and improve productivity by 5-50% (averaging 25%) due to wide canopy access [23]. Those platforms are no longer used, with the main reasons cited being labor availability and that platforms do not benefit experienced crews whose members are paid individually. However, according to the same author, this situation is currently changing due to labor shortages. Sanders (2005) noted that harvest efficiency evaluation is limited to the individual; for harvest-assist equipment use, group harvesting must be considered, which could be a limitation. Costa and Camarotto (2012) reported a similar situation regarding the use of a mobile platform for citrus harvesting. However, trained pickers showed a 60% increase in productivity. On the other hand, Cubero et al. (2014) and Vidal et al. (2013) described a mobile manual picking platform, where sorting was efficiently performed using a computer vision system, showing an improvement in this system [24].

Citrus harvesting has been extensively studied, particularly regarding mechanized harvesting. Whitney & Harrel (1989) provided a historical overview of citrus harvesting from the early 1960s, showing rising harvesting costs and dependence on manual labor. Essentially, the same principles of the mechanical harvesting system used then are still in use today, applying shake-and-catch systems. There are four main mechanical harvesting techniques for citrus: (a) air shaking, (b) trunk shaking, (c) limb shaking, and (d) canopy shaking [24,25]. Some of these are used not only for citrus but also for other crops. The shaking method is used for olives [26], pistachios [19], and apricots [11]. However, Roka and Hyman (2012) reported that mechanical citrus harvesting has declined in Florida, USA, in recent years, mainly due to tree damage, recovery time for the next harvest season, and increasing incidences of citrus greening disease. For citrus, none of the current mechanical harvesting systems are efficient, and an alternative is improving manual harvesting by increasing productivity [25]. None of the current systems can efficiently replace humans in terms of fruit selection capability [26]. However, different levels of impact on manual harvesting have been observed, especially when using fruit detachment instead of manual picking. Therefore, there is a clear indication for improving citrus harvesting [2,13,26].

2. Materials and methods

Mechanical harvesting of fruits and vegetables presents particular challenges such as: harvested products are highly variable in terms of agronomic, physiological, and structural characteristics, size, shape, detachment, etc.; harvesting machines must be highly specialized and are used for only a few hours per year; fruits and vegetables have been and still are harvested manually even in most developed countries, so labor issues usually arise when mechanization is introduced with the aim of improving economy and quality; factors such as suitable varieties, planting and scheduling systems, soil and irrigation management, material handling, grading and sorting, processing, and others—which themselves require considerable know-how and technical expertise—impose strict conditions on the viability of mechanical harvesting for any fruit or vegetable species.

The PESTKA fruit tree trunk shaker machine is designed for harvesting cherries, plums, apples for the food industry, olives, and other fruits intended for juices, cider, preserves, etc. PESTKA is a tractor-mounted unit equipped with a three-point hitch system and external hydraulic systems. The shaker machine grips the tree trunk with a clamping device and shakes it. The harvested fruits are collected in panels spread under the tree (panels are not included in the standard PESTKA equipment). The fruits must then be transferred to crates. All leaves and small branches must be removed with the help of a blower.
The PESTKA fruit tree trunk shaker machine uses the tractor's external hydraulic system, allowing for a simpler structure compared to similar devices from other manufacturers. The shaking efficiency can be adjusted by simply changing the mass of the rotating components of the shaker head. The length of the arm supporting the shaker machine is adjustable from 1200 to 2000 mm, making it easier to work in orchards with irregular spaces between rows. Due to the arm's 90° rotation to the right and left, harvesting from both sides of the rows can be done simultaneously. In this configuration, 2 sets of panels and 2 additional people are required to position them.

Figure.1 The PESTKA fruit tree trunk shaker machine [27]

The GACEK fruit tree shaker machine is designed to harvest not only cherries but also other stone fruits such as plums.The fruits are shaken from the tree, and all impurities such as leaves or twigs are removed with a blower, after which the fruits are collected in crates or pallet boxes. To achieve maximum working efficiency, proper orchard preparation is extremely important. This is a basic condition for the proper functioning of the GACEK fruit tree shaker machine. The trees must be maintained much taller than in an orchard designed for manual harvesting. The GACEK fruit tree shaker machine has adopted a modern solution – an inverted "umbrella" that opens hydraulically under the tree before shaking the fruits. To operate the GACEK machine, two or three people are required: a tractor driver and 1-2 people for handling the fruit tree shaker machine. The GACEK machine is particularly recommended for family farms with cherry orchard areas of up to 5 hectares. Under optimal conditions, the GACEK machine can harvest fruit at a rate of 50-60 trees per hour.

Figure. 2 GACEK Fruit Tree Shaker Machine [28]

The JAREK 5 is the latest version of the semi-ripe harvesting machine designed for collecting berries such as blackcurrants, red and yellow currants, honeyberries, autumn raspberries, saskatoon berries, rose hips, and haskap berries. JAREK 5 is a versatile harvesting machine that can be adapted to meet the specific needs of berry producers. It is characterized by high-quality finishes, a simple design, and ease of use. A significant change from previous versions is its modular design, allowing adjustments to meet customer needs and enabling configuration changes at a later date. The machine's transmission components are fully hydraulic, operated through the tractor’s PTO controller via a hydraulic pump device.

The JAREK design allows for the installation of either one or two shakers (to be decided by the customer when ordering), with the two-shaker version being more common. The dual-shaker design has shown better results with most berry varieties, harvesting more accurately and causing less damage to the bushes. A wide range of adjustments for the shaker elements and the possibility of low mounting in a "radial shape" allows for harvesting from both large and small bushes. Harvesting from very small bushes may result in lower accuracy. The "radial" shakers can be equipped with either metal fingers (20 pieces) or plastic fingers (24 pieces). The configuration of each harvester and its accompanying equipment is individually set according to the grower's needs.

Figure 3. JAREK 5 Semi-Ripe Berry Harvester Machine [29]

The OSKAR 4WD self-propelled harvester is the latest version of the harvesting machine for mechanical picking of berries on plantations specially prepared for this operation.
OSKAR 4WD is a complex, self-propelled harvester with hydrostatic four-wheel drive that collects fruit from the entire row. The working unit transmission is hydraulic. The drive on the front axle of the self-propelled harvester extends for harvesting (working position) and narrows in the transport position. This solution significantly improves the machine’s mobility on public roads and its operation on plantations. The conveyor belts that receive the fruit and the fans that remove impurities are hydraulically operated and have adjustable speeds. The asymmetric position of the shakers (the left one is shifted towards the right along the axis of the machine) and the use of an innovative hydraulic tilt adjustment system for the shaker device allow for customization of shaking for both tall and short bushes, enabling the harvesting of various types of berries, including raspberries on one-year-old canes. The OSKAR 4WD self-propelled berry harvester has been adjusted to harvest many types of berries by using different vibration parameters in terms of vibration amplitude. Lower amplitude is used, for example, during gooseberry harvesting, and higher amplitude for currant picking.

Furthermore, two types of shaking elements have been developed: metal fingers and plastic fingers. The use of double-unit fingers improved the mounting of the units on the column and allowed for an increased density of these fingers. This solution significantly increased the efficiency of harvesting fruit strongly attached to the buds (e.g., chokeberries when they have dried considerably). A new vertically adjustable locking unit has also been developed, with forced offset adjustment (articulated type) between the left and right transverse conveyor belt troughs.

Figure 4. Self-propelled harvester machine, OSKAR 4WD [30]

3. Results

MAJA Cherry, Sour Cherry, and Plum Shaking and Harvesting Machine. For traditional orchards, the MAJA shaking and harvesting machine is among the most commonly used. The harvesting process involves shaking the fruit onto a sheet spread on the ground using an agitator mounted on an arm. After rolling up the sheet, the fruit falls onto a conveyor and is transported through the cleaning unit, where impurities, including leaves and branches, are thoroughly removed.

Figure 5. MAJA Cherry, Sour Cherry, and Plum Shaking and Harvesting Machine [31]

Blackberry Harvester Machine KAREN 2 for 1 Row. KAREN 2 is a full-row harvester machine that attaches to a tractor using the three-point hitch system. It is equipped with two shakers with vertical fingers, featuring adjustable amplitude heads.

The KAREN 2 harvester machine is one of the machines designed for harvesting blackberries and raspberries. It is specially designed for blackberries and raspberries cultivated on trellises. [45]

Figure 6. Blackberry Harvester Machine KAREN, [32]

Self-propelled Cherry and Plum Harvester FELIX. The FELIX self-propelled harvester is a full-row machine designed for harvesting cherries, sour cherries, and plums in densely planted orchards. It is equipped with a sliding, comfortable cabin, control panel, and video system, ensuring comfortable operation.


Figure 7. Self-propelled Cherry and Plum Harvester FELIX, [33]

FELIX/Z Trailed Cherry and Sour Cherry Harvester. The FELIX/Z is a full-row trailed harvester designed for harvesting in densely planted orchards. Its vertical shaker system and efficient cleaning unit ensure high fruit quality. FELIX/Z is designed for orchards with trellis structures and properly trained trees. While primarily known for harvesting cherries and plums, it is also suitable for industrial apple harvesting. The FELIX/Z is a full-row, trailed harvester compatible with agricultural tractors of at least 80 HP. Its hydraulic-powered working units ensure efficient harvesting, high yield, and ease of use.


Figure.8. FELIX/Z Trailed Cherry and Sour Cherry Harvester, [34]

The VICTOR Z Harvester. The VICTOR Z is a specialized harvester for berries such as currants, aronia, gooseberries, blueberries, and cranberries. It is equipped with a V-shaped shaker system and a durable, efficient shaking head.

The VICTOR Z harvester is designed specifically for harvesting currants. The standard version collects berries into two 500 kg boxes or smaller boxes (10-20 kg) on each side platform. Berries are collected on two working platforms. The machine features special output conveyors for collecting berries into two 500 kg boxes on the left platform and two 500 kg boxes on the right platform. Efficient collection into standard 10-20 kg boxes is also available as an option. Boxes are unloaded from the platform manually or using other machines. The crop height must be up to 2.2 meters, with a minimum row spacing of 3.5 meters.


Figure .9. The VICTOR Z Harvester, [35]

4. Conclusions

In-depth research on different types of harvesting machine collection devices is useful for solving problems related to safety hazards, low harvesting efficiency, high fruit damage, unreasonable collection device size, and improper human-machine relationship matching.

Efficient fruit harvesting without damaging the tree requires selecting the appropriate harvesting technology based on: tree characteristics – type, size, natural frequency, damping properties, and tree architecture; fruit properties – shape, size, stem length, and maturity level; and vibration techniques – type of shaker, mass, amplitude, excitation frequency, and clamp position.

Although mechanical harvesting increases harvesting efficiency, it has disadvantages, which may include tree injuries, fruit damage, debris and litter, the need for specific orchard design and tree preparation, significant capital investment, and machine maintenance costs.

Recent advances in sensing and machine vision techniques have significantly improved automation in new mechanical harvesters, increasing the efficiency and productivity of these machines. Growers can benefit from smart harvesting systems that rely less on operators. Additionally, because harvesters are expensive and used for no more than two months a year, much of the tree crop harvesting is contracted to commercial services, making harvest timing an important parameter.

This analysis discusses current mechanical harvesting technologies for selected temperate and tropical fruit and nut trees, factors affecting mechanical harvesting, smart harvesting techniques and challenges, and provides an overview of mechanical harvesting and its future prospects.

The development direction of precise harvesting, non-destructive transport, and high-efficiency technologies in fruit harvesting operations is continuous innovation and the promotion of mechanized and intelligent operations, which can not only improve production efficiency but also enhance product quality, increase economic benefits, and create favorable conditions for competition and cooperation in the international fruit market.

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Review

ASPECTS REGARDING ACTIVE AERATION IN MODERN GRAIN PRESERVATION AND STORAGE SYSTEMS

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Keywords: *storage systems, grains, aeration, metal silo*

Abstract: The mechanical ventilation of grains is a modern conservation and storage system, which replaces traditional drying, through the natural ventilation of the warehouses. The normal preservation of grain depends on a whole series of variables. Aeration can be designed to suit a variety of storage types, including grain sheds, bunkers and most silos. Correctly aerating and managing stored grain will minimize the risk of insect infestation and damage This paper presents some principles of grain management uses active aeration to control grain temperature and to reduce moisture variations for the purpose of maintaining the quality of stored products.

1. Introduction

As agricultural production increased from year to year, the need for methods to store and transport large quantities of grain developed. More and more farmers prefer to keep the grains obtained from their own productions, in order to capitalize on them at the best possible price, for their own consumption or for the establishment of new crops, without taking on the task of maintaining unaltered properties of biological value, of improving those of cultural value, of carrying out appropriate treatments against diseases and pests [1-3].

Because agricultural grains are biological materials that interact with their immediate environment they must be stored and transported using methods that preserve quality as seeds, food stuffs, or raw materials. Proper management throughout the harvesting, cleaning, drying, conveying, and storage processes maintains grain in its proper state for use [4,5].

Grain is often harvested at a moisture content that is too high for safe storage. Drying is the most common post-harvest process performed for the long-term preservation of grain. Grain quality is significantly affected by the drying process and type of dryer. Various numerical models have been developed to simulate the drying process of agricultural grains based on either heat and mass balances or systems of differential equations [6-8].

The safety of cereal grains after harvesting is a key issue for farmers and consumers. Cereals can become infected by fungi that form mycotoxins under certain weather conditions. Due to climate change mycotoxins in cereals should be monitored carefully [9].

The mechanical ventilation of grains is a modern conservation and storage system, which replaces traditional drying, through the natural ventilation of the warehouses. The normal preservation of grain depends on a whole series of variables. Grains that have reached maturity show high moisture and enzyme activity to match, while sprouted grains are characterized by high respiration energy. Grain storage during periods with low temperatures is done in closed warehouses, equipped with active ventilation systems, located at floor level or below it [10-12].

By active aeration is meant the forced introduction of a current of cold or dry air into the seed mass to replace the air in the intergranular space that has become stale and warm because of the breathing effects of all its living components [13-15]

The introduction of cold air contributes to cooling and equalizing the temperature of the seed mass (the main purpose of active aeration), thus reducing the vital activity of its components.

The introduction of dry air reduces the relative humidity of the intergranular air, reduces the humidity of all components which also reduces the physiological activity, prevents the migration and accumulation of moisture in certain areas and prevents overheating.

This paper presents some principles of grain management uses active aeration to control grain temperature and to reduce moisture variations This paper presents some principles of grain management uses active aeration to control grain temperature and to reduce moisture variations for the purpose of maintaining the quality of stored products.

2. Materials and methods

Flat bottom silos offer a cost-effective solution for long-term storage, which safely protects the quality of grains for a prolonged period of time ensuring the best quality of grains are offered to end-users. As compared to the conical silo, the flat-bottom silo has a lower cost of storing. Thus, the flat bottom silo is one of the most convenient options for long-term grain storage. Silo cell-type storage systems are provided with those necessary for active aeration and with spreading devices designed to prevent self-sorting [16-19].

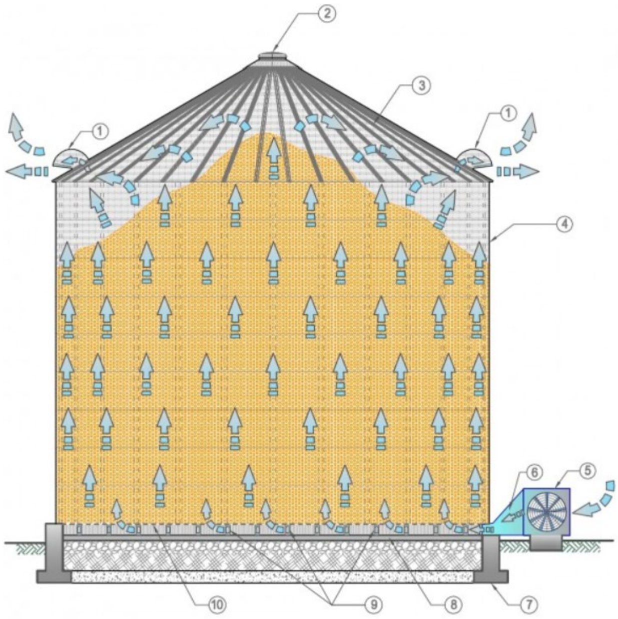


Figure 1. Silo-type storage cell with flat bottom, [20]

1- air vent; 2 - feeding zone; 3 - silo roof; 4 - silo's wall; 5 - fan; 6 - adapter; 7 - the foundation of the silo; 8 - circular concrete plate; 9 - floor supports; 10 - fully perforated floor

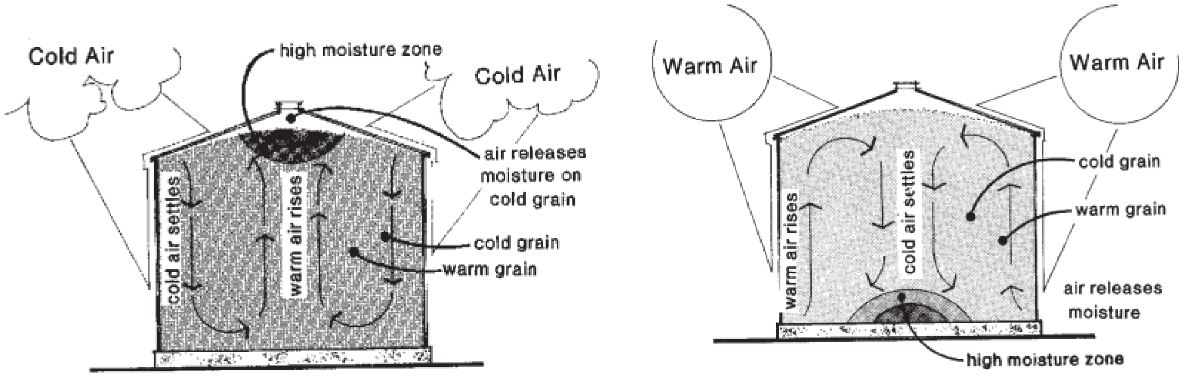
Metal silos with flat bottoms (figure 1) are used to store grain for the long term, having various aeration options, such as: fully perforated floor or channels with perforated plates, air vents, fans for grain aeration. Also, flat bottom silos can be equipped with monitoring and control system, such as sensor cables for measuring temperature and humidity, but also determining the concentration of carbon dioxide in the grain column and the level of the product in the cell.

Mobile electric ventilators are used to blow air, with capacities and pressures appropriate to the storage capacity of the cells. In these cells, the air is introduced through the lower part with the help of flexible tubes and removed through the covers on the upper part.

It is recommended that active aeration should also be done in the cell loading flow, i.e. start as soon as the product layer has covered the distribution channels and continue throughout the filling period. In this way the seeds that fall like rain have fuller contact with the breathed air, they dry or cool down more easily. When aerating the storage cells, it is necessary to recirculate the seed at certain intervals in order to counteract the tendency of veins to form in certain directions, through which the air would flow more easily, without cooling the mass of seeds. By recirculating a quantity of seeds (for example a one meter layer) the veins are broken and aeration is made easier.

Grain temperature and moisture migration

More dried grain goes out of condition because grain temperatures are not proper controlled. The temperature inside the bin causes moisture to move or migrate from one part of the grain mass to another, where the moisture can accumulate and cause grain spoilage problems. Although moisture migration problems can occur any time grain temperatures vary considerably, the most critical time occurs when warm grain is stored in cold winter temperatures [21-23]. In the fall, when the air temperature cools down, the grain along the bin wall cools more quickly than the rest of the grain. The difference in temperature starts air moving down the bin wall and toward the centre of the bin. As the air moves through the grain it becomes warmer and begins to pick up moisture from the grain. When the warm moist air hits the cool upper surface of the grain, condensation occurs (Figure 2 a). In the spring the problem is reversed. Warming action from the sun on the outside of the bin causes moisture currents to move up and into the bin. Condensation then occurs on the bottom of the bin (Figure 2 b).



a *b*

Figure 2. Moisture migration inside the bin, [21]
a - in winter; b - in spring

Aerate for grain temperature control

Modern grain management uses aeration to control grain temperature and to reduce moisture variations. Aeration forces air through the grain either continuously or intermittently. Aeration is not a grain drying system and should not be used as one. Grain drying or rewetting is usually insignificant during grain aeration, because the cooling (or warming) front moves through the grain about 50 times faster than a drying or wetting front. Grain can be tempered (cooled or warmed) by either negative or positive aeration systems. With either system, a tempering (cooling or warming) zone moves through the grain. The movement of the tempering zone completely through the grain is one cooling or warming cycle. Once a cycle had been started, operate the fan continuously until the zone moves completely through the grain. The time required to complete each cycle depends almost entirely on the aeration airflow rate.

In a positive pressure system (Figure 3), the tempering zone starts at the bottom of the bin and moves up. When moving air upwards, aeration progress can be easily determined by checking the grain temperature at the top centre. Also, with an upward airflow, the fan can be started immediately and air leaving the duct will keep the perforations clean.

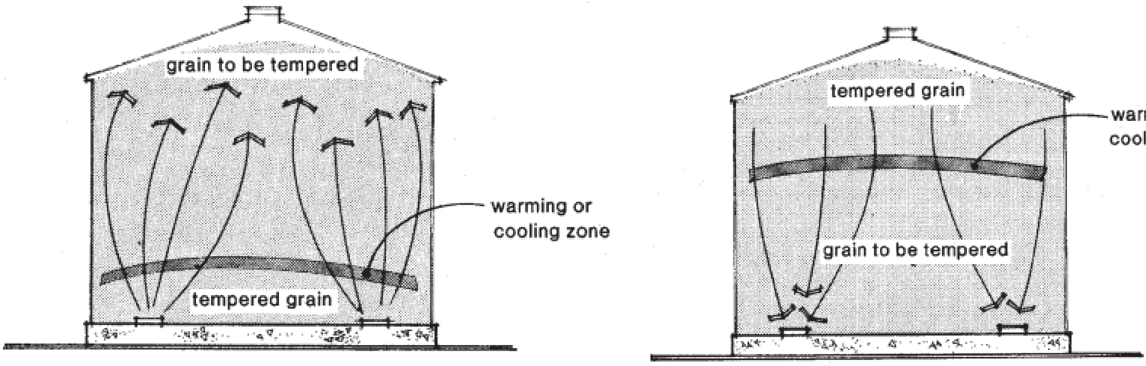


Figure 3. The movement of the tempering zone through the grain, [21]

In the negative pressure system, the tempering zone starts at the top of the bin and moves down. The main advantage is to minimize roof condensation when aerating warm grain in cold weather. The uncertainty of knowing when aeration is complete is the main disadvantage, since the grain at the bottom is the hardest to check.

Peaking grain in storage

Most dry grain will form a peak at an angle of 16°÷20° when centre filling without a distributor. Although it is tempting to store those extra bushels, they can interfere with uniform aeration and add to the moisture migration problem. Peaking also makes it difficult and dangerous to enter the bin for observation. Because of dust and high temperatures during the summer, never enter the small space between roof and grain. Shifting grain may block the exit. If the grain has peaked when filling the bins at harvest, remove the grain in the peak immediately for long-term storage. Lowering the centre cone of the bin improves air flow through the centre and probing and sampling are made easier and safer. Some fines will also be removed.

Managing fines in storage

Broken grain and foreign material can create two problems in stored grain, particularly when they accumulate in pockets. First, broken kernels are more susceptible to spoilage than unbroken ones. Secondly, airflow from aeration fans tends to go around pockets of fines so they cool more slowly. The pockets often develop into hot spots that result in spoiled grain. Serious efforts should be made to reduce the fines produced by harvesting, drying and handling, rather than trying to resolve storage problems later. Three grain storage management techniques that reduce the problem from fines are as follows:

- Use a grain spreader to minimize the concentration of fines in storage.
- Clean the grain before binning to improve storability.
- Remove grain from the centre a few times during filling to remove accumulated fines.

Temperature sensing

Consider installing temperature sensing units in large grain storages. Temperature sensors accurately trace the progress of aeration cooling or warming cycles. They help identify hot spots within the grain mass [24-27].

Insect control in stored grain

Insect infestations in storage can come from grain residues in combines, handling equipment, and from old grain left in storage. Correctly drying, aerating and managing stored grain will minimize the risk of insect infestation and damage. Insect activity goes with moisture accumulation and grain heating. Look for insect activity on every storage visit. If an insect problem is noted, fumigate with a liquid, solid or gas grain fumigant in storage or as the grain is being turned. Fumigants are toxic and must be applied with proper safety precautions and equipment [28]. New methods, such as cold plasma, infrared radiation and microwave heating used in the grain industry for insect control during storage are becoming a safer tool for the disinfestation of stored grains [29]. The new techniques are rapid and can be applied to bulk material without affecting the quality of grains.

Aeration can be designed to suit a variety of storage types, including grain sheds, bunkers and most silos. It is also often retrofitted to older silos. The four main components are fans, ducting, roof vents and a reliable method for automating fan run times when cooler, dry air is available. A good-quality automatic aeration controller is recommended as the most reliable method of ensuring fans are running at optimum times [30].

Aeration cooling aims to push a series of 'cooling fronts' through grain, starting from the base of the silo (See Figure 4).

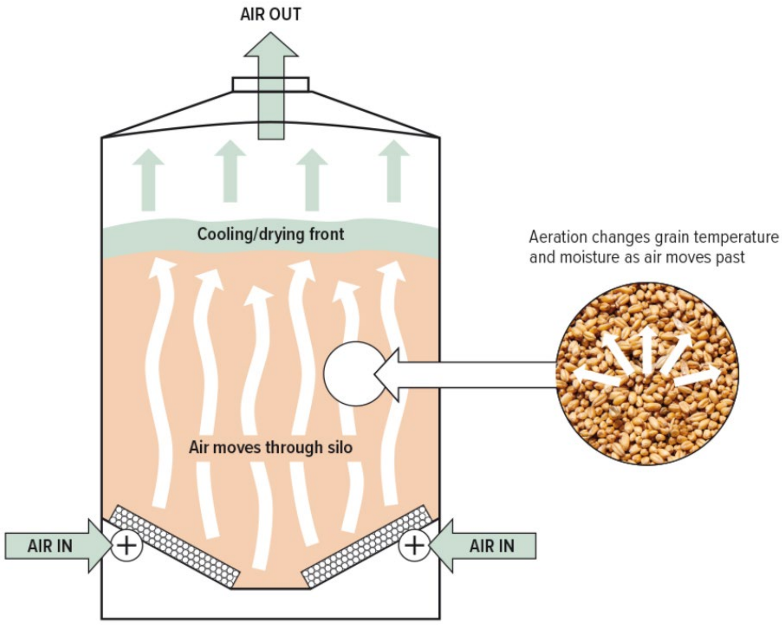


Figure 4. Cooling/drying fronts in the aeration process, [15]

3. Results

Figures 5 and 6 below show the impact of storage temperatures (30°C and20°C) and grain moisture content (10, 12, 13, 14, 15% m.c.) over time on the germination viability of wheat seed.

Clearly, storing dry seed (10÷12% m.c.), under cool conditions (15÷20 °C), are worthwhile targets to aim for to maintain seed germination quality.

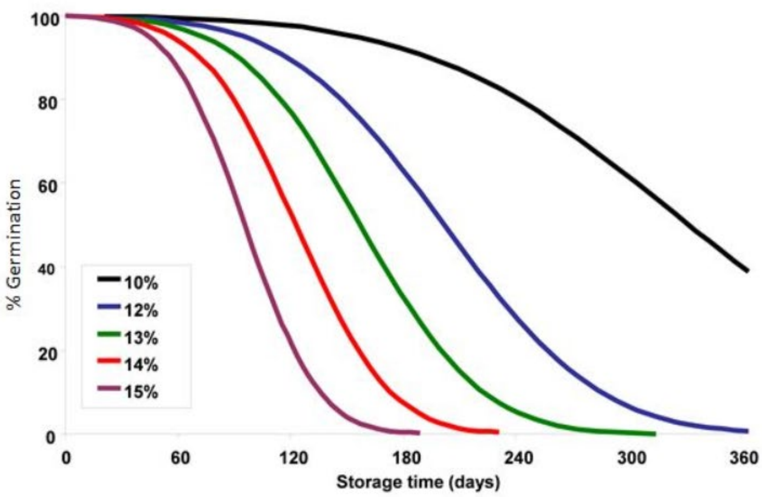


Figure 5. Influence of moisture contents (10 to15%) on percentage gemination of wheat stored at 30°C, [21]

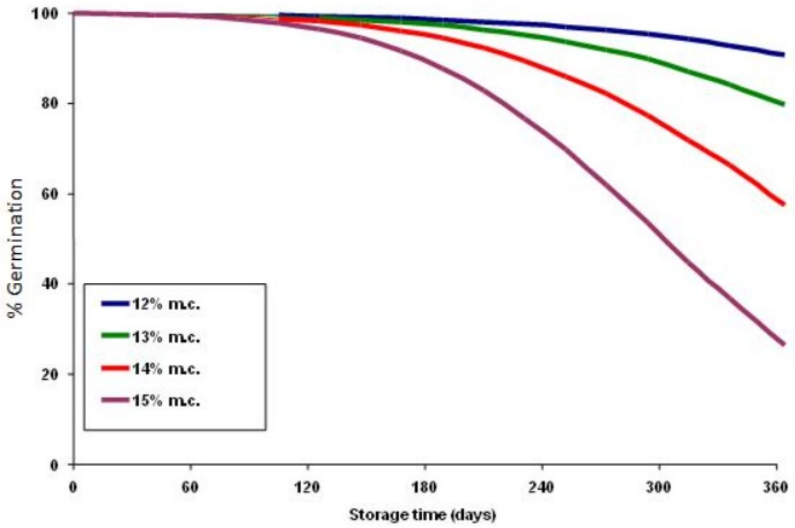


Figure 6. Influence of moisture content (12 to15%) on percentage germination of wheat stored at 20°C, [21]

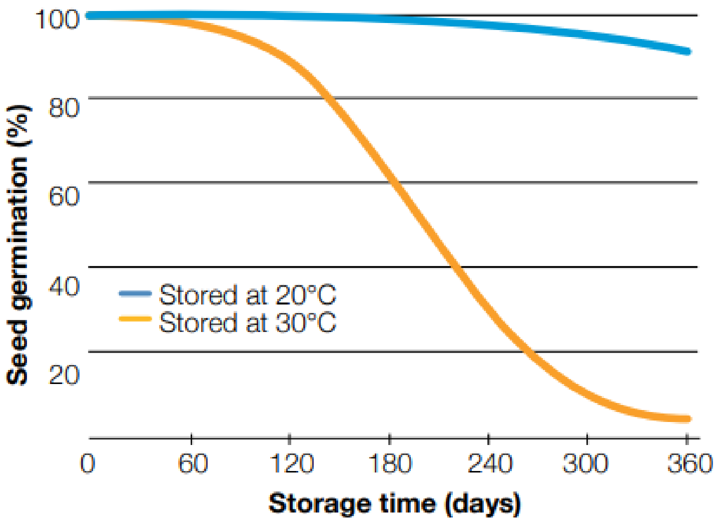


Figure 7. Influence of temperature on wheat germination stored at 12% moisture content [31]

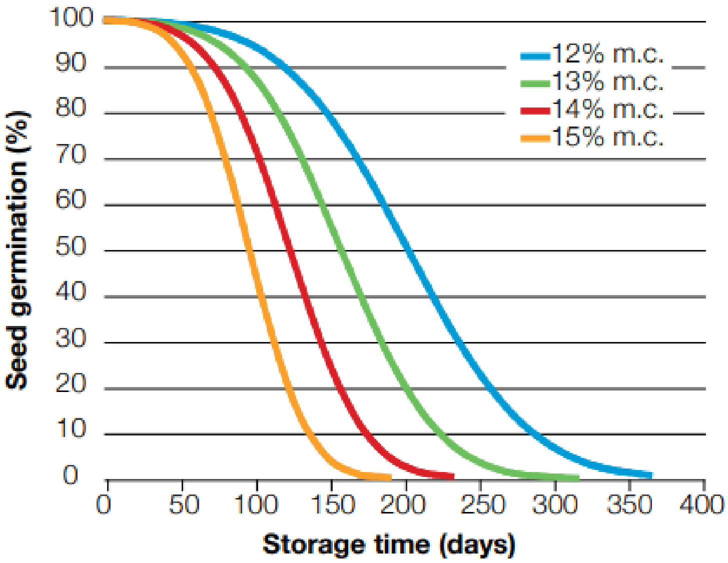


Figure 8. Influence of moisture content (m.c.) on germination of wheat stored at 30°C [21]

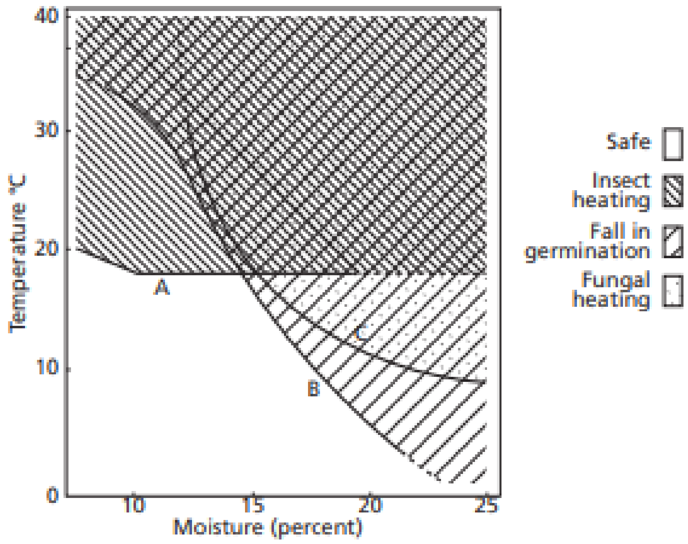


Figure 9. Effects in storage at different temperatures and moisture content [31]

Drying of cereals at low temperatures, compared to drying at high temperatures, has low energy consumption and the quality of the dry product is better. The cooled products do not have to be moved, which leads to energy savings and the reduction of losses due to grain breakage during grain handling. Cereals have excellent thermal insulation properties and are self-insulating; for this reason, the dangerous heat inside the bulk of uncooled grain cannot escape to the outside, and this fact allows for repeated cooling of the products at a certain water content.

The preservation of grains by active aeration consists in the periodic exchange of the intergranular air in the mass of grains with atmospheric air, in exchange for reducing their temperature, with all the effects it has. The method has the advantage that, using cold air, it ensures the increase of the preservation period and the maintenance of the qualitative characteristics of the cereals. During active aeration, there is a heat and mass transfer that leads to the establishment of a hygrometric balance between the product and the intergranular air. The method is used in all silos equipped with cells and special aeration installations.

4. Conclusions

For grain storage management it is important:

- ✓ Have a good quality seeds that are properly dried and cleaned (poor quality seed loses its viability even when stored under ideal storage conditions).
    - High moisture causes heating, which encourages growth of seed-borne fungi and increased insect activity. As a rule of thumb, for seed m.c. between 5% and 14%, each 1% reduction in m.c. approximately doubles seed storage life.
    - A good storage facility maintains good quality seeds with high viability and vigor.
- ✓ Maintain the ideal temperature and relative humidity inside the storeroom.
    - Increase in temperature and humidity can cause seed deterioration and promote proliferation of seedborne pathogens and stored grain insect pests.
    - As a rule of thumb, each 5°C decrease in storage temperature between 0°C and 50°C approximately doubles seed storage life. When storing seeds under ambient condition, the storage room should be provided with adequate ventilation.

Conflicts of interest: The authors declare no conflict of interest.

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Review

ENERGY SOURCES USED IN THE FRAMEWORK OF MECHANIZATION TECHNOLOGIES FOR THE RECONSTRUCTION AND MAINTENANCE OF PERMANENT PASTURES

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Keywords: *agricultural tractors, mechanization, meadows*

Abstract:
The mechanization of agricultural work on permanent pastures is of particular importance in reducing physical effort to produce high-quality and inexpensive forage. To enhance the ecological and economic significance of natural forage lands, the use of energy sources adapted to the terrain's topography is necessary, especially on slopes in hilly and mountainous areas, which play a rather important role in the exploitation of permanent pastures. The research results presented in this work provide useful recommendations for farmers who wish to use energy sources adapted to mechanization technologies for the rehabilitation of pastures in Romania, aiming to increase their pastoral value, both for the exploitation of the potential of this forage resource and for maintaining their multifunctionality.

1. Introduction

Due to improper management, grasslands in general, and permanent grasslands in particular, often necessitate interventions focused on improving the living conditions for valuable grassland plants, without compromising the existing vegetative cover [1]. These include fundamental works to increase the production and quality of grasslands, which are simple, easy to apply, and in most cases, less costly if a long-term monitoring plan is implemented. This plan should start with restoration activities and follow the recovery process [2]. This category encompasses technically and culturally complex works, including overseeding, control of woody vegetation, improvement of nutrient regimes, enhancement of moisture regimes, and prevention and control of soil erosion [3].

On a farm, it is essential, first and foremost, to equip it with the necessary energy sources to operate the machinery, installations, and technical equipment intended for carrying out works aimed at improving the floristic composition and productivity of permanent grasslands [4]. Equipping a farm with the necessary energy sources is done based on the pedoclimatic conditions of its location, the level of electrification, size, financial capabilities, primary profile, and the availability of labour during agricultural campaigns [5]. For the aggregation of agricultural machinery for the mechanization of operations in permanent pastures [6] the following sources of energy are used:

- **single-axle tractors** for performing work on small farms in hilly and mountainous areas;
- **standard tractors** adapted to work on slopes of up to 12º (21%);
- **special tractors** for agricultural machinery used on slopes ranging from 19...22º (35...40%);

- self-propelled machines specialized particularly for fertilization and forage harvesting on slopes steeper than 19...22º (35...40%).

2. Materials and method

The materials and research methods involve the use of reading materials (from international scientific databases such as Thomson ISI, ScienceDirect, SpringerLink, CABI, ELSEVIER/SciVerse SCOPUS, Google Scholar, etc.) for the implementation of the research phase titled 'Study of the energy base for mechanizing operations on degraded pastures' within the project 'ADER 15.3.2 - RESEARCH ON THE DEVELOPMENT AND PROMOTION OF MECHANIZATION TECHNOLOGIES FOR THE RECONSTRUCTION, MAINTENANCE OF PERMANENT PASTURES, ENVIRONMENTAL PROTECTION, AND BIODIVERSITY MAINTENANCE, USING NEW SPECIFIC EQUIPMENT,' carried out under the ADER program, contract number ADER 15.3.2.

3. Results

Tractors for the mechanization of agricultural work on farms

a) Use of single-axle tractors

Single-axle tractors serve as the primary energy source for small farms located in hilly and mountainous areas. These tractors have a power range of 4.40 to 6.82 kW (6 to 12 HP) and are designed to mechanize agricultural and household tasks on farms with arable land areas of 2 to 5 hectares. In households in mountainous regions, they are essential equipment.

Increasing the power of the single-axle tractor to 8.8-12 kW (12-16 HP) has significantly broadened its range of applications. Currently, when combined with various machines, this tractor can perform the following tasks: soil work (ploughing, milling, harrowing, discing, cultivating, burying, ridging, etc.); fertilization work; seeding work; pesticide application work; forage harvesting work (mowing, raking, etc.); transportation work; farm and household tasks, and more.

The single-axle tractor Kubota U30 (fig.1) manufactured in Shandong, China, is available in three different models: Kubota U30-6 (6×4), Kubota U30-10 (10×4), and Kubota U30-15 (15×4). Each model has its specifications based on the size of the KUBOTA (Japan) engine, weight capacity, fuel tank size, and other factors.

Figure 1. Single-axle tractor Kubota U30 (Source: https://www.made-in-china.com/products-search/hot-china-products/Kubota_Walking_Tractor.html)

b) Standard use tractors

- **SOLIS 20 4WD AGRICULTURAL TRACTOR**

The Solis 20 4WD agricultural tractor (fig. 2) is powered by a diesel engine, specifically the Mitsubishi MVL-3E model, boasting a maximum power output of 20 HP and a 4x4 traction capability. The braking system is of the dry drum type, and the brake actuation is mechanical.

Figure 2. The agricultural tractor Solis 20 4WD (Source: https://padure-gradina.ro/produs/tractor-agricol-solis-20-4wd-20cp/)

Technical specifications

Engine power, HP	20	Model series	3
Rear tires	8.00-18	Front tires	5.00-12
Transport length, meters	2.75	Transport width, meters	1.197
Transport height, meters	1.95	Gearbox type	6 forward / 2 reverse
Weight, tons	0.885	Engine manufacturer	Mitsubishi

- **30 HP agricultural tractor, TYM T303 HST**

The TYM model T303 HDT (fig. 3), produced by the TYM company, is a 30 HP tractor crafted for agility and versatility. This sub-compact tractor offers enhanced maneuverability, ensuring effortless operations. Hydrostatic steering controls and accelerator levers facilitate precise control over the tractor's direction and engine speed. Additionally, a dedicated PTO lever enables control over the direction and speed of the implement.

Figure 3. 30 HP agricultural tractor, TYM T303 HST (Source: https://www.olx.pt/d/anuncio/trator-tym-t303-c-alfaias-IDHKBXw.html)

Technical specifications

Engine power, HP	30	Model series	3
Rear tires	9.25/14	Front tires	600/14
Transport length, meters	2.74	Transport width, meters	1.34
Transport height, meters	2.47	Gearbox type	12/12
Weight, tons	1.15	Engine manufacturer	Mitsubishi

- **35 HP agricultural tractor König Traktoren 354, 4x4**

The König Traktoren 354, a 35 HP 4x4 tractor (fig. 4), is equipped with a direct injection diesel engine featuring four cylinders for efficient fuel consumption and high torque. The gearbox provides 8 forward speeds and 2 reverse speeds, ensuring optimal efficiency during operation.

Figure 4. 35 HP König Traktoren 354 tractor (Source: https://agromarksrl.com/product/tractor-konig-traktoren-354-35-cp-4x4/)

Technical specifications

Engine power, HP	35	Model series	3
Rear tires	11.2x24	Front tires	7.0x16
Transport length, meters	3.140	Transport width, meters	1.34
Transport height, meters	2.22	Gearbox type	8+2
Weight, tons	1.39	Engine manufacturer	König Traktoren

- **Agricultural tractor IRUM TAG 24RH – 24 HP**

The agricultural tractor, IRUM TAG 24RH (fig. 5), is equipped with a 24 HP diesel engine, making it well-suited for small farms and various tasks such as mowing and raking. This tractor features a hydrostatic transmission with 2 ranges, providing an unlimited variable speed from 0 to 21.4 km/h. It is designed with two directional pedals for use with the right foot; the left pedal controls the forward movement, while the right pedal controls the reverse movement. The clutch operates on a dry single-disc type mechanism.

Figure 5. Agricultural tractor IRUM TAG 24RH (Source: https://www.tehagropiese.ro/produs/tractor-agricol-irum-tag-24rh-24-cp-13000-eurotva/)

Technical specifications

Engine power, HP	24	Model series	3
Rear tires	11.2x20	Front tires	7.0x16
Transport length, meters	3.122	Transport width, meters	1.419
Transport height, meters	2.321	Gearbox type	4+4
Weight, tons	0.956	Engine manufacturer	Branson

Wheel tractors of 45-53 HP

Agricultural tractor Foton FT454 (45HP)

The Foton FT454 tractor (fig. 6) is equipped with a water-cooled, four-cylinder diesel engine with 45 HP. It distinguishes itself from other similar types through a series of advantages, such as compactness, ease and speed of handling, significant transport power, and convenience in maintenance.

Figure 6. Foton FT454 tractor (Source: https://agrorid.com/en/ft454/)

Technical specifications

Engine power, HP	45	Model series	3
Rear tires, mm	1220..1300	Front tires, mm	1300
Transport length, meters	3.98	Transport width, meters	1.620
Transport height, meters	2.50	Gearbox type	4+4
Weight, tons	1.97	Engine manufacturer	FOTON 454

Agricultural tractor Forte Forte XD 454, 45 HP, 4x4

The 45 HP Forte XD 454 tractor (fig. 7) features a 4x4 traction system and is suitable for agricultural work in pastures and meadows. The tractor can be equipped with a full range of accessories, having a power take-off (PTO) and hitch for various attachments.

Figure 7. 45 HP Forte XD 454 tractor (Source: https://www.agronord.ro/product/tractor-agricol-forte-454-45-cp-4x4/)

Technical specifications

Engine power, HP	45	Model series	3
Rear tires	11.2-24	Front tires	7.50-16
Transport length, meters	3.558	Transport width, meters	1.50
Transport height, meters	2.245	Gearbox type	4x4WD
Weight, tons	2.2	Engine manufacturer	FORTE

- **Agricultural tractor TAG 50C IRUM, 48 HP**

The TAG 50C tractor (fig. 8) is equipped with a 48 HP diesel engine, designed for light agricultural tasks. Additionally, it is recommended for work in greenhouses, nurseries, and horticultural activities.

Figure 8. TAG 50C tractor (Source: https://www.irum.ro/lista-de-utilaje/tag-50c/)

Technical specifications

Engine power, HP	48	Model series	3
Rear tires	13.6-26	Front tires	9.50-16
Transport length, meters	3.421	Transport width, meters	1.642
Transport height, meters	2.463	Gearbox type	4x4WD
Weight, tons	2.2	Engine manufacturer	Fiat

Wheel tractors of 65-68 HP

- **Agricultural tractor STEYR – KOMPAKT S, 58 – 65 HP**

The Steyer company produces the Kompakt S model, renowned for its outstanding maneuverability and superior visibility among machines in its class. Combining the economy, lightweight nature, and agility of small-sized equipment, it also boasts the spaciousness, reliability, and power typical of large tractors. This makes it the ideal versatile machine for agricultural farms, animal farms, and pastures.

Technical specifications

MODEL	4055 KOMPAKT S (fig. 9)	4065 KOMPAKT S (fig. 10)
ECE R1201) [kW / hp]	43 / 58	48 / 65
CAPACITY [cm3] / Number of cylinders	3.400 / 4	3.400 / 4

Figure 9. 4055 KOMPAKT S Tractor

Figure 10. 4065 KOMPAKT S Tractor

Source: https://www.wylzeagro.ro/tractor-steyr-kompakt-s)

John Deere 5065 E Tractor 65 HP

The John Deere 5065 E Tractor (fig. 11) is ideal for small farms and meets all the reliability, performance, and productivity conditions required for daily and specialized activities. The equipment is characterized by a powerful, reliable, and efficient PowerTech M engine equipped with three cylinders and water cooling. The integrated turbocharger provides additional power, increasing the capacity to handle heavy tasks. The tractor's transmission is robust and capable of handling all the tasks it is subjected to. The nine forward speeds (three reverse speeds) are well synchronized, and the power transfer is well optimized.

Figure 11. John Deere 5065 E Tractor |(Source: https://www.trigreenequipment.com/new-equipment/utility-tractors/5e-series-50-100-hp-/5065e-cab/)

Technical specifications

Engine power, HP	65	Model series	5E
Rear tires	420/85 R30	Front tires	320/85 R24
Transport length, meters	3.89	Transport width, meters	1.81
Transport height, meters	2.46	Travel speed, km/h	28
Transmission	9/3	Weight, tons	2.745
Three-point category	2	Engine manufacturer	John Deere

TRACTOR LINDNER LINTRAC 75 LS

The Lindner Lintrac 75 LS tractor (fig. 12) is a versatile machine designed for alpine mountain agriculture and pastures. The tractor is notably lightweight, maneuverable, and stands out with its powerful hydraulic system. The 3.6-liter Perkins Syncro engine in Stage 5 offers high torque.

Figure 12. Lindner Lintrac 75 LS Tractor (Source: https://niro-stahl.ro/utilaj/lindner-geotrac-64ep/)

Technical specifications

Engine power, HP	76	Model series	Lintrac
Rear tires	420/85 R 30	Front tires	375/70 R 20
Transport length, meters	3.505	Transport width, meters	1.968
Transport height, meters	2.450	Travel speed, km/h	40
Three-point category	2	Weight, tons	3.35
Engine manufacturer	Perkins	Size (lxwxh), mm	667x564x789

Wheel tractors of 80-100 HP

- **TRACTOR LINDNER LINTRAC 80**

The Lindner Lintrac 80 tractor (fig. 13) is equipped with a Perkins Syncro Stage 5 engine with a capacity of 3.6 liters and 100 kW (equivalent to 102 HP), as well as an enormous torque of 550 Nm. The Lintrac 80 is the most powerful tractor offered by Lindner, featuring four-wheel steering on demand. Lindner has further developed the stepless TMT11 IF transmission from the Lintrac 110. The high traction mode increases the traction force up to eight kilonewtons. The front axle with suspension is standard with the 50 km/h version. The TracLink system makes the Lintrac 80 the smartest vehicle from Lindner in its class.

Figure 13. Lindner Lintrac 80 Tractor (Source: https://www.lindner-traktoren.at/en/tractors-transporters/tractors/lintrac-80)

Technical specifications

Engine Power, HP	102	Model Series	Lintrac
Rear Tires	420/85 R 30	Front Tires	375/70 R 20
Transport Length, meters	3.61	Transport Width, meters	1.97
Transport Height, meters	2.453	Travel Speed, km/h	40
Three-Point Category	2	Weight, tons	3.92

Special tractors for powering agricultural machines working on sloping terrains.

ISODIAMETRIC MULTI-FUNCTIONAL TRACTOR WITH REVERSIBLE SEAT FOR SLOPED LAND IN HILL AND MOUNTAIN AREAS, BETTER BRAND (ITALY)

The multi-functional tractor BETTER 175 (fig. 14) is unique on the market and should not be missing from the equipment of any medium and large farm in Romania because:

- it is equipped with equal wheels and low ground clearance, providing unparalleled stability on sloping terrains in hilly and mountainous areas;
- it has a reversible control station, allowing reverse driving, so that the implements attached to the rear linkage will be in front of the operator for better work and increased comfort;
- it has 3 steering modes: with the front axle, with both axles, or crab mode, which enhances stability when working on sloping terrains.

Figure 14. BETTER 175 Tractor (Source: https://agridin.ro/produs/bm-tractors-better-175/)

Technical specifications

Engine Iveco Fpt	4 Cylinders 4500 cc
Engine Power	125 kW la 2200 rpm
Driving Position	reversible
Air Seat	adjustable
Number of Wheels	4
Control Valve	with Hydraulic Action
P.T.O (Power Take-Off), rot/min	540/1000
Lifter	electronically operated

The use of specialized self-propelled machines for carrying out specific tasks or groups of tasks on sloping terrains

For the mechanization of agricultural tasks such as the management of chemical and organic fertilizers, harvesting forage, and transporting various products on terrains with slopes greater than 19^0 (35%), specialized self-propelled machines have been developed. These machines are capable of working typically on slopes up to 31^0 (60%) and, in extreme cases, up to 39^0 (80%). This involves the improvement of mowers on single-axle tractors, collectively referred to as single-axle trimmers, the development and improvement of trimmers with two axles, and the creation of self-propelled chassis for slopes. These machines can operate a range of equipment such as those for fertilizing with chemical and organic fertilizers, gathering, loading, and transporting forage, and transporting various materials, among other functions.

REFORM MACHINERY

The company Reform produces machinery specifically (fig. 15) designed to work on very steep slopes, whether in agriculture or soil care. Their very low center of gravity provides them with maximum working angles of up to 45 degrees.

Technical specifications

	Metrac H75 (fig. 16)
Power, kW/HP	55.2 / 75
Weight, kg	2500
Wheelbase, mm	2150

Figure 15. Self-propelled Metrac H75 equipment equipped with the SM 210 FK-S mower (Source: https://landwirt-media.com/reform-metrac-h75-die-neue-generation/)

CONCLUSIONS

The research results offer valuable recommendations for farmers seeking to employ energy sources tailored to mechanization technologies for pasture rehabilitation in Romania. The objective is to enhance the pastoral value of these pastures, tapping into the potential of the forage resource and preserving their multifunctionality.

ACKNOWLEDGEMENT

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Review

TRANSFORMING AGRICULTURAL WASTE INTO RESOURCES: TECHNOLOGIES AND PRACTICES FOR SUSTAINABLE CIRCULAR FARMING

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Keywords: *Agricultural waste, Circular economy, Biomass, Resource reutilization, Smart waste systems, Waste management technologies.*

Abstract: Agricultural waste, a by-product of agricultural and industrial activities, poses a substantial challenge in the effective management of natural resources and the mitigation of environmental impacts. The most notable examples of such waste materials include plant residues, animal manure, food processing residues and other organic materials. These are most commonly discarded or incinerated, resulting in detrimental effects on air, water and soil quality. However, the implementation of innovative and sustainable solutions, such as the recycling and valorisation of agricultural waste into bio-energy, composts and natural fertilisers, has the potential to enhance the efficiency and environmental responsibility of the agricultural sector. This article paper examines the sources of agricultural wastes, their environmental impact, and the necessity to develop sustainable agriculture that minimises waste and promotes the use of resources in a circular way. The paper further presents novel technologies and waste management strategies that can convert waste into valuable resources, thereby supporting the development of a more sustainable and resilient agricultural system.

1. Introduction

Rapid population growth is exerting significant pressure on the agricultural sector to meet the increasing global demand for food [41]. The latest United Nations report estimates that the global population will exceed 8.5 billion in 2030, 9.7 billion in 2050, and could reach a peak of approximately 10.4 billion around 2080 [31]. This growth is expected to be particularly pronounced in emerging countries such as Mexico, India, China and others [19]. The issue of population growth in the poorest countries is a major challenge for governments as they attempt to implement the 2030 Agenda for Sustainable Development. This international plan of action aims to eradicate poverty and hunger, to improve health and education systems, to promote gender equality, and to reduce inequality around the world [50]. Global agricultural production currently reaches 23.7 million tons of food daily, and this growth has contributed to environmental degradation, endangering soil, air, water resources, ecosystems and human health [41]. Global resource utilization, inefficient waste management and pollutant emissions have contributed to significant increases in climate change and environmental degradation [51].

Agriculture is the second largest contributor to greenhouse gas emissions (19.9%), after the energy sector (68.1%), and produces a significant amount of solid waste [5]. Sustainable agriculture plays a crucial role in protecting the environment and biodiversity. The "transition to sustainability" in agriculture signifies the transformation of the agricultural system into a more integrated and sustainable model [20]. A more relevant definition of sustainable agriculture emphasizes human intent, concisely reflected in the legal concept of "usufruct", which, in Thomas Jefferson's time, referred to "the right to use and profit from a resource without impairing the substance of that resource. Sustainable agricultural practices and approaches provide solutions for producing food and other agricultural products with low environmental impact, without jeopardizing access to and availability of food and the long-term well-being of future generations [42].

With increasing demands for food, energy and resources due to population expansion, ensuring the continuous functioning of production systems becomes crucial. In line with the principles of environmental sustainability, the agricultural sector needs to embrace waste recovery and cost-efficiency analysis, implementing circular economy (CE) as an alternative to conventional agriculture, which uses resources in a linear fashion [17].

The issue of waste management is becoming increasingly problematic as a result of rising consumption levels. Global waste generation reached 2.02 billion tons in 2016 and is projected to reach 3.4 billion tons by 2050. The value of the waste management market was USD 1.61 trillion in 2020 and is projected to reach USD 2.5 trillion by 2030, underscoring the significant challenges confronting humanity in the management of these materials [4]. The volume of agricultural waste is increasing annually due to the expansion of the farming industry, and the recycling rate remains low. If not adequately managed, it has the potential to contaminate the environment and compromise human health. However, the nutrient content of these materials renders them a valuable resource for the production of organic fertilisers, provided they are subjected to proper treatment [28]. Globally, China, the USA and India are the largest producers of agricultural waste [27]. Every year, India produces a considerable amount of solid waste, of which agricultural waste accounts for the largest share, reaching between 350 and 990 million tons annually [25]. India is the second largest producer of agricultural waste, generating over 130 million tons of rice straw. About half of this is used for animal feed and the rest is discarded. [21]. Pakistan generates over 20 million tons of waste annually, 60-65% of which is organic and biodegradable. Agricultural waste is often burned or destroyed due to lack of proper disposal facilities [53].

A country's income is closely linked to its agriculture, which has a considerable impact on national GDP. Large economies like the United States and the European Union are investing heavily in innovative agricultural technologies. By 2050, the majority of the population is expected to live in cities, and agricultural productivity will need to increase by 70% to meet food demand [26]. Both developed and developing countries are implementing policies and allocating enormous resources to tackle the persistent problem of increasing waste generation and disposal [4]. Despite efforts to reduce greenhouse gas emissions, global emissions exceeded 50 Gt CO_2-eq per year in 2017, and projections suggest that the carbon budget needed to reach the 1.5°C target could be exhausted in less than a decade [56].

This article examines the growing challenge of agricultural waste management, driven by increasing global agricultural production and waste generation. It focuses on the environmental risks, particularly the release of greenhouse gases due to inefficient waste disposal practices. The paper highlights the importance of waste recovery and recycling, especially for producing organic fertilizers, essential for sustainable agriculture. It explores modern technologies like composting, anaerobic digestion, pyrolysis, and waste-to-energy (WtE), which convert agricultural waste into valuable by-products such as biogas, biochar, and compost, thus reducing environmental impact. The article also evaluates advanced waste management solutions aligned with circular economy principles, aiming to minimize waste, improve resource recovery, and lower the ecological footprint of agriculture. Ultimately, it demonstrates how these strategies support a shift to a more circular, eco-efficient agricultural system, benefiting both the environment and human health [17, 26, 35].

2. Sustainability and circularity

The "take, make, and dispose" (TMW) model is an unsustainable system that wastes the planet's increasingly scarce resources, used in most of the world's economies to meet food, energy and water needs [3]. It is now recognized that it needs to be replaced by the concept of "resource, recovery and recycle" for sustainable development. This concept helps in limiting the consumption of virgin resources and efficient utilization of waste materials [35].

In circular economy, the aim is to improve the continuous flow of technical and biological materials in the value circle by avoiding, reducing, reusing and recovering waste or recycling it completely. At global level, significant action plans have been implemented, such as the Law on the Promotion of Circular Economy in China and the EU Report on the Implementation of the Circular Economy Action Plan [13]. The notion of a circular economy was first coined in the 1990s by China and subsequently adopted by the European Commission under the Green Deal programme. The Ellen MacArthur Foundation has been instrumental in promoting this approach on a global scale [56].

The notion of a circular economy is an emerging field of enquiry, and while its potential to contribute to sustainable development is recognised, the relationships between sustainability and circular economy, practical implementation, and quantitative evidence of positive economic, environmental, and social impacts are still under-explored. The implementation of the circular economy is constrained by biophysical limitations, including the significant energy demands for resource recovery, the deterioration in resource quality, and the perpetual demand for extraction of virgin resources. Additionally, the complexity of resources, comprising both organic and inorganic components, further complicates the process [51]. These initiatives are backed by instruments such as taxes, financial subsidies and specific indicators to support the transition towards a more sustainable economic system [12]. The following image illustrates the core principles of the circular economy, highlighting its role in creating a sustainable and efficient economic system.

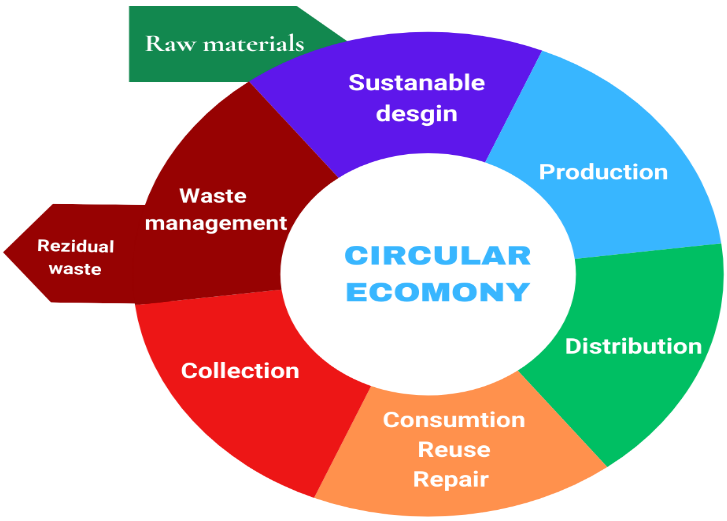

Figure 1. The Circular Economy model (adapted from [12])

The transition to a circular economy has the potential to generate employment opportunities, encourage innovation, and reduce consumer costs by offering more sustainable products. The European Union's strategic objective is to transition towards a circular and climate-neutral economy by the year 2050. This ambitious commitment is underpinned by a comprehensive legislative framework encompassing various key areas, including eco-design, packaging, recycling, and other pivotal sectors [12].

The notion of global food security is a multifaceted concept, encompassing several fundamental dimensions: food availability, which refers to the quantity, quality and diversity of food resources; accessibility, which ensures that food can be obtained in an economical and physical way, especially for vulnerable populations; utilization, which addresses the nutritional quality of food and the ability of people to consume and benefit from it; stability, which ensures constant and continuous access to food; resilience, which reflects the ability of food systems to cope with and recover from external shocks, such as climate change or market instability; and sustainability, which promotes responsible resource management and the long-term protection of biodiversity [39].

3. A taxonomy of waste and residue types derived from the agricultural and food processing sectors.

Globally, large amounts of agricultural wastes are generated annually, especially rice straw (731 million tons) and industrial wastes [37]. In this context, it is essential to identify economical solutions for crop residue utilization in order to reduce the negative impact of burning and environmental degradation in the open air [5].

Agricultural development, through the uncontrolled application of intensive methods and the excessive use of chemicals, often leads to the generation of waste, with a negative impact on the rural and global environment. Agricultural waste originates from diverse activities, including land cultivation, animal husbandry and aquaculture. Its management is guided by the "3R" (Reduce, Reuse, Recycle) strategy [36]. The nature of these by-products varies according to the specific stage of the agricultural process, including the handling of agricultural products, animal husbandry, as well as their preparation, production, storage, processing and consumption. Consequently, these by-products are valorised in diverse manners to encourage more sustainable development [41].

Agricultural waste is a term given to a variety of materials. These include animal manure and carcasses (animal waste), corn stalks, sugar cane bagasse, defective fruits and vegetables, plant cuttings, as well as pesticides, insecticides and herbicides, which are considered hazardous and toxic wastes [8]. Wastes that affect sustainability also include crop residues (leaves, stems, straw), animal wastes (urine, droppings, waste milk), poultry wastes (spilled feed, feathers, droppings), slaughterhouse wastes (blood, hides, bones), agro-industrial wastes (bagasse, molasses, fruit peels) and aquaculture wastes (unconsumed feed, faecal wastes [21]. Agricultural waste biomass comprises cellulose, hemicellulose and lignin, which can be differentiated into wastepaper, wood waste, grasses, etc. [23]. Excesses from the growing and processing of raw agricultural products, including fruits, vegetables, meat, poultry, dairy products and crops, are generally categorised as agricultural waste. These by-products, arising from the manufacturing and processing of agricultural products, may contain materials that could be advantageous to humans. However, their economic value may be less than the costs associated with their collection, transportation and processing [9, 47].

Agro-industrial waste is defined as organic waste resulting from various agricultural and industrial activities. Such activities include, but are not limited to, animal excreta in the form of slurry and manure, used mushroom compost, dirty water, silo effluent and others. These wastes are divided into three main categories: natural (plant) wastes, animal wastes and vegetable wastes. In industrial contexts, such as fish processing, palm oil, biochemical and rubber processing, the management of these wastes is a frequently analysed topic [44]. Agro-industrial waste comprises a wide range of materials that constitute a significant source of agro-industrial biomass. This waste contains compounds such as cellulose, hemicellulose, lignin and extractives, in varying quantities [24]. Despite the challenges associated with the management of these wastes, they can be recycled through physical or biological methods, thereby extracting non-natural materials and transforming them into a valuable resource. Consequently, through effective management and integration into a circular economy system, agro-waste can contribute to reducing negative environmental impacts and support a more sustainable agricultural system. Agro-waste is categorised into two broad classifications: agro-waste (from agricultural fields) and industrial residues (from the processing of raw materials). Agro-waste includes field residues, such as husks, stems and leaves, and process residues, such as seeds left after crop processing. Industrial waste can be defined as waste material that is produced during the course of industrial manufacturing processes, with examples of such waste materials including potato peelings, soybean oil cakes and orange peel waste from the fruit juice production industry [16, 24]. The following image showcases the various types of agro-industrial waste, illustrating their potential for recycling and reuse in sustainable agricultural practices.

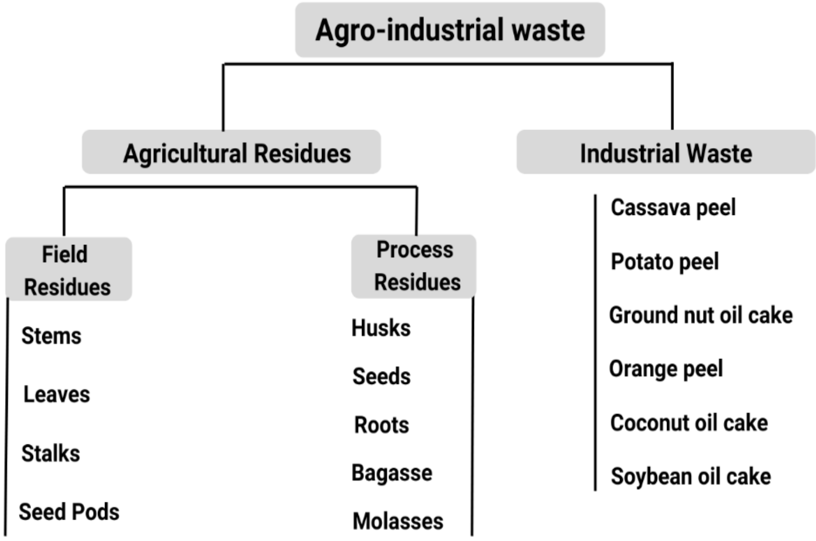

Figure 2. Agro-industrial waste and their types (adapted from [5])

Agricultural waste originates from a variety of sources, with the most significant losses of food and nutrients occurring in relation to cereals and legumes, fruits and vegetables, meat and animal products, and roots, tubers and oilseeds. Of these, roots, tubers and oilseeds account for approximately 26%, and fruits and vegetables for around 22%, representing the most substantial sources of food waste [8]. Cereal crops are a significant source of agricultural waste, with some being utilised for animal feed, composting, or energy production [3]. Rice, a crop of global importance, produces rice hulls, which are a significant waste, especially in major producing Asian countries such as China, India and Indonesia. Furthermore, approximately 60-70% of the global sugar is derived from sugarcane, a process which generates bagasse and other solid waste [9].

Definitions of food loss and wastage vary between different institutions and are not always uniform. According to the Food and Agriculture Organization (FAO) and the Economic Research Service of the U.S. Department of Agriculture, food loss and food wastage refer to the decrease in edible food mass. In contrast, agricultural wastes and by-products are typically defined as plant or animal residues that are not (or are no longer) utilised for food or feed. These include non-food by-products arising from agricultural production and processing. These by-products can impose a significant economic and environmental burden on agricultural and primary processing sectors, with the impact being further exacerbated by regional specialisation in crop or livestock production [21]. The reduction of food loss and wastage (FLW) has become a global priority with the establishment of the United Nations Sustainable Development Goal 12.3, which aims to halve food loss by 2030. In numerous developing countries, the reduction of food loss has the potential to enhance nutrient availability, thus assisting in the fight against hunger and malnutrition, particularly in low-income areas. Moreover, a reduction in FLW would also be expected to have a positive effect on producer incomes and result in a decrease in consumer spending. It is imperative to recognise food losses as an integral component of agri-food systems, and to formulate integrated solutions that address these losses, encompassing the entire production to consumption continuum. Such an approach is essential for ensuring efficient resource management and mitigating environmental impacts [3, 11].

4. Emerging technologies and modern methods in agricultural waste management

Solid waste management encompasses the identification, recycling, collection and disposal of solid waste. The primary technologies employed in the management of agricultural waste are landfill and incineration. Nevertheless, due to the uncontrollable nature of these processes, which can generate emissions of toxic gases or leachates, they frequently result in substantial environmental pollution. It is estimated that approximately 3-4% of global greenhouse gas emissions are attributable to inadequate waste management practices [40, 52]. The following figure illustrates the utilization of agro-waste for various end-use applications, highlighting how these materials can be repurposed for purposes such as bioenergy production, organic fertilizers, and other sustainable products.

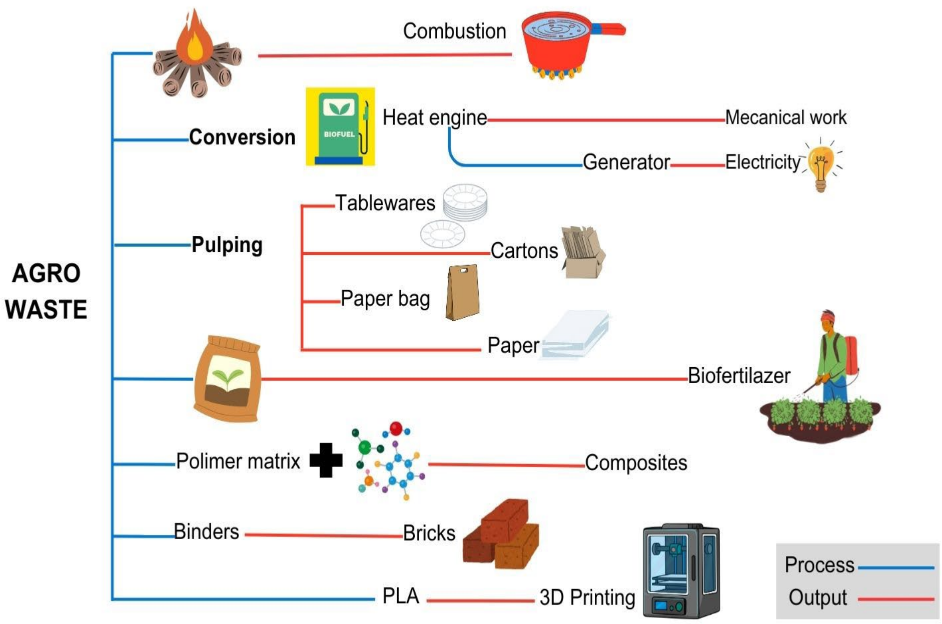

Figure 3. Agro-waste utilization for various end-use applications (adapted from [16])

Instead, innovative technologies, such as thermal conversion, anaerobic digestion and aerobic composting, are increasingly being used to valorise agricultural waste [54]. Agro-industrial wastes can also be directly processed through thermo-chemical processes such as combustion, gasification, liquefaction and pyrolysis [24].

Furthermore, the implementation of bio-based agricultural waste management (ABM) strategies constitutes a pivotal approach to averting the inefficient utilisation of animal manure and the combustion of crop residues. These strategies contribute to food and health security while promoting the valorisation of agricultural waste into value-added products. By converting agricultural waste into useful products, economic opportunities are created, such as increasing farmers' incomes, generating jobs for young people and supporting agricultural sustainability. Agro-waste can also be easily decomposed and the resulting products, such as biofertilizers or biochar, will provide essential nutrients for plants, thus improving soil structure by increasing porosity, aeration and water retention capacity [21]. Researchers continue to explore how to valorise agro-waste to produce sustainable and innovative products, including biodiesel, bio-hydrogen, biogas, bricks, biodegradable cutlery, particle boards, baskets, earth cups, candies and banana stem juice, thus promoting a circular economy and a cleaner, healthier environment [16].

Waste to Energy (WtE) can be defined as an innovative approach to waste management, based on the idea that energy sustainability requires both clean energy sources and sustainable energy systems. The processing of waste results in the production of solid fuel, while the conversion of waste into biogas or syngas, or the incineration of waste for energy generation, is also a key component of the process [43].The following figure illustrates how the use of Waste-to-Energy plants in the EU helps in saving fossil fuels, demonstrating the potential of waste management technologies to contribute to energy production and reduce reliance on non-renewable energy sources.

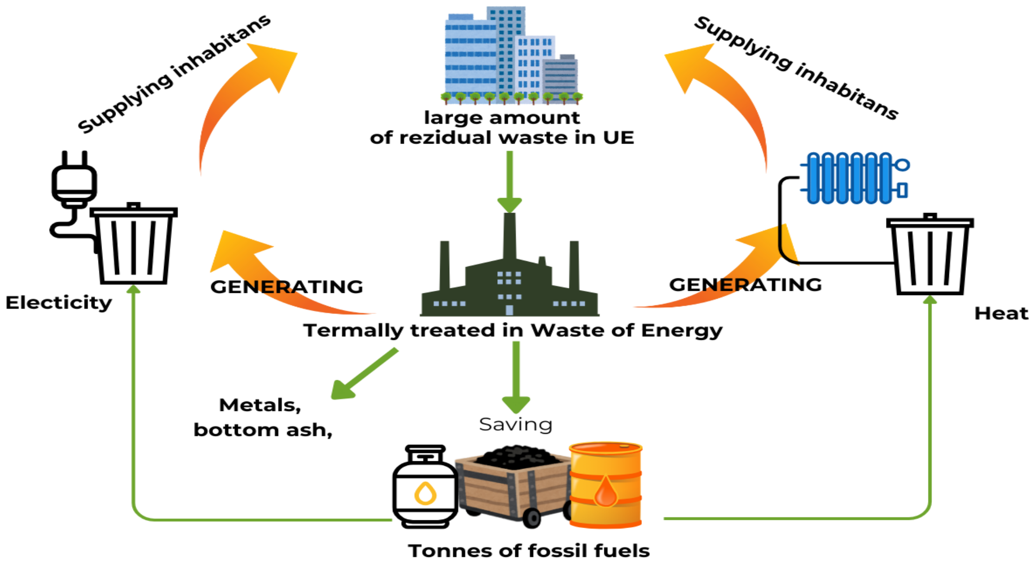

Figure 4. Saving fossil fuels in the EU through the use of Waste-to-Energy plants
(Adapted from [59])

The Waste to Energy (WTE) principle entails the conversion of municipal solid waste (MSW) into useful energy through incineration, with the flue gas being cleaned (FGC) to reduce air pollution. The emission of nitrogen oxides (NOx) is regulated through the implementation of SNCR (injection of ammonia solution directly into the afterburner chamber) and SCR (injection of ammonia solution into a catalytic reactor) technologies. These technologies have been shown to have a significant impact on the reduction of NOx and dioxin emissions. Consequently, WTE plays a pivotal role in the sustainable and efficient recovery of energy from waste, thereby minimising its environmental impact [59].

Pyrolysis

The process of dry-heat degradation is defined as the decomposition of biomass that occurs at elevated temperatures (550-850 °C) in an oxygen-free or inert gas environment. The outcome of this process can be the conversion of agricultural waste into biochar, biogas and bio-oil, depending on the reaction conditions [54]. The following figure illustrates the biomass pyrolysis process, showcasing how organic materials are converted into valuable products such as biochar, bio-oil, and syngas through thermal decomposition in the absence of oxygen.

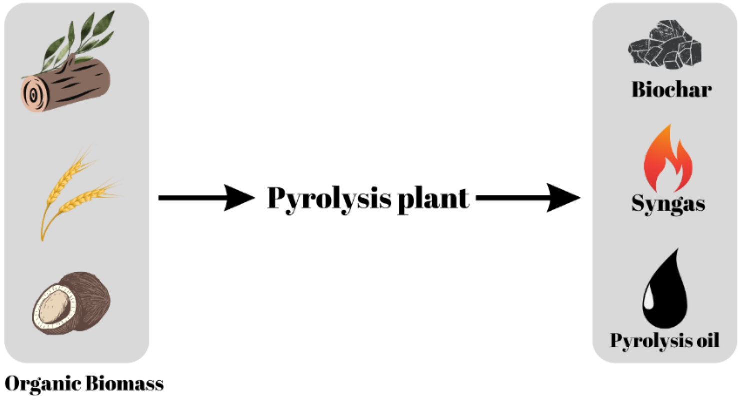

Figure 5. The biomass pyrolysis process
(adapted from [67])

Rapid pyrolysis produces bio-oil and gaseous co-products from agricultural residues. Biomethane can replace diesel engines and its use in waste management policies increases demand for the resource. Although bio-oil can reduce fuel costs, its quality needs to be improved and methane engine technology is still under development and further research is needed [40]. Pyrolyzing agricultural wastes to obtain biochar is also a preferred solution for sustainable waste management [5].

Anaerobic digestion

Plant residues and agricultural waste can be turned into biofuels, an environmentally friendly alternative to fossil fuels. These wastes can be used to produce biogas through anaerobic digestion, which helps reduce greenhouse gas emissions and generate clean energy. Biogas from agricultural waste can be used to produce electricity, heat or as fuel for vehicles, contributing to a cleaner environment [15]. The following figure illustrates the stages of anaerobic digestion, showing how organic matter is broken down to produce biogas, digestate, and other secondary products derived from both.

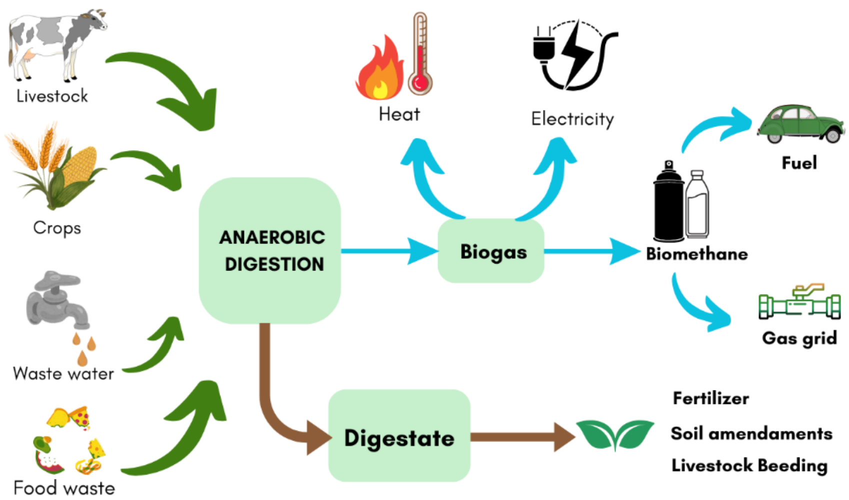

Figure 6. The stages of anaerobic digestion (adapted from [59])

Regarding the management of manure, methane (CH_4) and nitrous oxide (N_2O) emissions account for a substantial proportion of global non-CO_2 greenhouse gas emissions. In confined animal production systems, these emissions can exceed 50%. In Denmark, for instance, 80% of manure is managed as sludge, and the use of technologies such as anaerobic digestion can significantly reduce these emissions [30]. China, a significant producer of agricultural and livestock products, generates substantial amounts of waste that can be utilised in anaerobic digestion processes for biogas production, thereby contributing to both pollution reduction and renewable energy generation. Consequently, effective management of agricultural and animal waste emerges as a pivotal strategy in the fight against climate change and the pursuit of a circular economy [49].

Biorefining

This approach is environmentally friendly and sustainable, with the objective of producing a wide range of fuels and commercial products. The production of bioenergy and biomaterials plays a pivotal role in addressing the escalating demand for petroleum products, and waste, which is often regarded as low value, becomes a valuable source of feedstock in biorefinery. The biorefinery process entails the conversion of biomass into energy and other valuable products, with the primary benefit being a reduced environmental impact by virtue of a decrease in emissions of pollutants and hazardous substances. According to the International Energy Agency (IEA), biorefinery is defined as the sustainable transformation of biomass into a variety of commercial products and energy sources. In an ideal biorefinery process, both energy and non-energy products are produced. The commitment to sustainability is reflected in the reduction of waste and the promotion of circular economy principles [3, 52]. The following figure illustrates the process of biorefining, showing how biomass is converted into a range of valuable products, including biofuels, electricity and other bio-based materials.

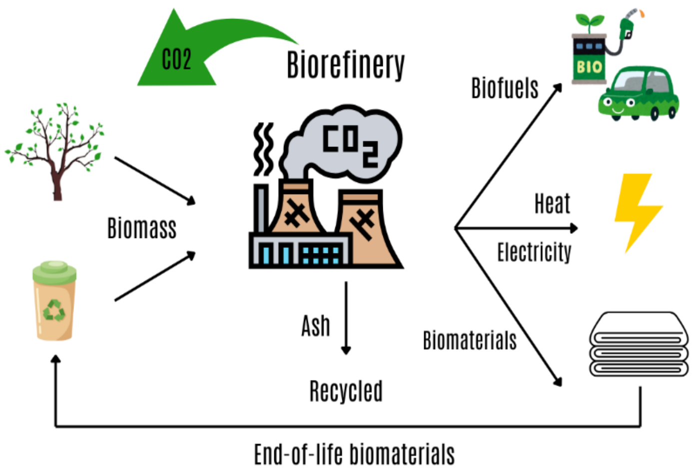

Figure 7. The process of biorefining (adapted from [65])

A biorefinery is a facility that combines biomass conversion processes and equipment to obtain fuels, energy and value-added chemicals from biomass. It operates along the lines of oil refineries, which produce several types of fuels and products from crude oil. By producing the various products, the biorefinery valorises the different components of biomass and their intermediates, thus maximizing the value obtained from the biomass feedstock [65].

Composting

It is one of the most efficient methods of organic waste management, relying on biological decomposition by microorganisms that regulate physico-chemical parameters such as temperature, humidity, aeration and C:N ratio [53]. This technique transforms agricultural waste into soil fertilizer, but agricultural residues can also be valorised by bioconversion to produce second-generation biofuels, briquettes or biogas, thus contributing to the development of a circular economy [3]. In this process, organic waste reduces its weight and volume by 50-65%, pathogenic bacteria are destroyed and nutrients are conserved, generating stable organic matter. The following figure illustrates the compost cycle, showing how organic matter is decomposed to produce nutrient-rich compost, enriching soil and supporting sustainable agriculture.

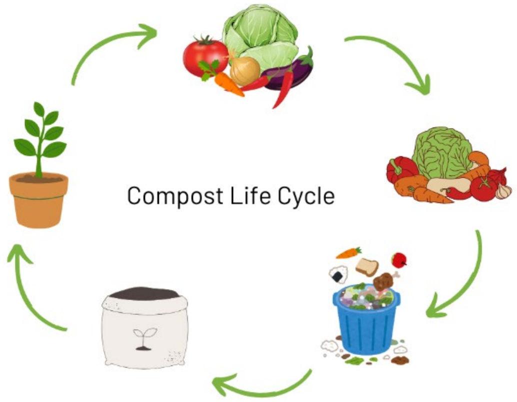

Figure 8. Compost cycle (Adapted from [66])

Aerobic composting is a simple and cost-effective method with low energy consumption, producing compost that can be directly returned to agricultural lands, reducing the need for chemical fertilizers [54]. However, traditional composting has several significant drawbacks, including the requirement for large areas, long fermentation cycles, and air pollution during the process. Additionally, the process may result in the production of lower-quality products, and incomplete decomposition along with low temperatures can affect efficiency. Conventional aerobic composting can lead to the emission of harmful gases such as NH3 and H2S, and carbon and nitrogen losses are substantial. However, by applying treatments at higher temperatures, pathogens can be destroyed much more rapidly, within just 10-30 minutes [28].

Solid-state fermentation (SSF)

It is a biotechnological process in which microorganisms grow on solid substrates such as cereals, straw, plant residues, or agro-industrial waste, under conditions of low or nearly absent moisture. This method is used to produce valuable products such as biofuels (bioethanol, biogas), enzymes, vitamins, antioxidants, bioactive compounds, and composts [44]. One of the major benefits of SSF (Solid-State Fermentation) is the utilization of agro-industrial waste that would otherwise be discarded or burned, transforming it into useful products. For example, residues from food processing, such as fruit pulp, rice straw, or coffee grounds, can be valorised to produce bioethanol, biofuels, or for eco-friendly treatments, such as removing heavy metals from wastewater [10]. Thus, SSF contributes to the development of a more environmentally friendly and sustainable agro-industrial system, reducing pollution and supporting circular economies. Additionally, SSF plays a crucial role in reducing energy consumption and greenhouse gas emissions, supporting the transition towards renewable energy solutions. Solid-state fermentation is also efficient for valorising lignocellulosic waste, which has low economic value, such as straw or cereal husks, for the production of bioethanol and biogas [44]. Furthermore, the microorganisms used in SSF are typically safe, and the products obtained do not contain toxins, making them safe for both animal and human consumption. The SSF process includes several stages: substrate preparation, microorganism inoculation, fermentation, followed by processing and packaging of the final product. Factors influencing the success of this process include substrate moisture, particle size, temperature, aeration, and the type of microorganisms used [47]. The chosen substrate depends on its cost, availability, and chemical composition, while microorganisms are selected based on the desired product. Thus, SSF represents a promising waste recycling method that helps manage agro-industrial waste, reduce pollution, and produce valuable products, contributing to sustainable economic development [55].

As highlighted earlier, waste recycling technologies, including pyrolysis, anaerobic digestion, biorefining, solid-state fermentation, and composting, are crucial for achieving sustainability. They reduce waste volumes, conserve natural resources, and produce renewable energy, supporting the circular economy. These processes contribute to environmental protection, reducing greenhouse gas emissions, and enhancing resource use efficiency, thereby promoting a more ecological and sustainable system. At the same time, pellets made from organic materials represent another sustainable solution for waste management and soil quality improvement. The process of producing pellets involves transforming agricultural waste and organic materials, such as straw, cottonseed hulls, or chicken manure, into a concentrated product that can be used both as a fertilizer and an energy source. For instance, chicken manure pellets are an excellent source of essential plant nutrients, such as nitrogen, phosphorus, and potassium, which are gradually released into the soil, thus supporting healthy plant growth without polluting the environment. Unlike fresh chicken manure, which can bring excess nitrates to the soil and negatively impact the environment [29, 61]. Through the recycling of organic waste into pellets, the process significantly contributes to sustainability by reducing waste and pollution. Biomass pellets help improve soil structure, increase water retention capacity, and protect the soil from drought. Pellet production equipment are essential for valorising these resources, which would otherwise contribute to pollution. They transform materials such as straw or rice husks into a renewable and eco-friendly fuel, thereby reducing dependence on fossil fuels and carbon emissions [29, 62]. Thus, the use of pellets made from organic materials not only supports soil and plant health but also represents an efficient method for reducing pollution and managing agricultural waste. The following figure illustrates the technological process for producing pellets from agricultural waste, highlighting the steps involved in converting biomass into efficient, compact fuel.

Figure 9. Technological Process for Producing Pellets from Agricultural Waste [62]

Green materials significantly contribute to addressing the issue of agricultural waste, as they utilize agricultural by-products such as rice straw, coconut fibres, or peanut shells, which would otherwise end up in landfills or be burned, generating pollution. By transforming these wastes into useful materials for construction, the negative environmental impact is reduced while existing resources are valorised. These materials can be used in various applications, such as thermal and acoustic insulation in construction, furniture products, building panels, as well as in the automotive industry or as eco-friendly packaging materials. Their utilization helps promote a circular model, where waste becomes a resource, thereby supporting a greener and more sustainable economy [18]. Creative recycling of waste reduces environmental impact and conserves natural resources, thus contributing to the construction of eco-friendly homes. Sustainable materials, such as FSC-certified wood and geopolymer concrete, not only reduce carbon footprints but also bring long-term financial savings, making eco-friendly buildings an ethical and economic choice. Additionally, these materials significantly reduce environmental impact due to the lower resource and energy requirements for their production. Buildings that use sustainable materials, such as bamboo or FSC-certified wood, contribute to the protection of ecosystems and biodiversity [62]. At the same time, rice husks, an often overlooked agricultural waste, have become a valuable resource in various industries, particularly in construction. Rice husk ash (RHA), obtained through the combustion of rice husks, is used as a partial substitute for cement [9]. Rice husks are also used in animal feed, as a construction material, fertilizer, and even in ethanol production, with recent research suggesting the potential for transforming them into useful products such as activated carbon or sodium silicate [14, 22]. Rice straw, rich in cellulose, hemicellulose, and lignin, can be converted into biofuels and biomaterials, thus contributing to the reduction of greenhouse gas emissions and improving agricultural productivity [23, 38]. Therefore, recycling rice husks not only protects the environment but also supports the circular economy by transforming waste into valuable resources.

Wheat straw, sugarcane bagasse, and corn stover are also examples of agricultural residues that can be efficiently recycled to produce valuable products and contribute to energy sustainability. Wheat straw, due to its high content of cellulose, hemicellulose, and lignin, can be used as an adsorbent material for removing pollutants from the environment or as animal feed supplements due to its fibre content [23]. Sugarcane bagasse, which is rich in polysaccharides, can be used for electricity generation in cogeneration plants, and the reuse of the resulting ash can help reduce issues related to the disposal of waste from sugar production [9]. Additionally, corn stover, an easily available agricultural residue, can be transformed through biochemical and thermochemical methods into energy sources, thus reducing environmental impact and offering an eco-friendly option for agricultural waste management [23,38]. These practices not only help in the efficient management of resources but also support the transition to more sustainable agriculture.

5. Artificial intelligence for sustainable agriculture

Artificial Intelligence (AI) has a significant impact on sustainable agriculture by optimizing resource use and reducing waste. Through the analysis of data from soil, weather, and crops, AI can accurately predict the needs of crops, helping farmers save water, nutrients, and fertilizers. Thus, AI not only improves agricultural production efficiency but also contributes to the conservation of natural resources and environmental protection by ensuring the rational use of resources [38].The Internet of Things (IoT) technology also plays a crucial role in transforming traditional agriculture. By using sensors and smart devices connected to IoT networks, farmers can monitor and control critical parameters for plant growth, such as temperature, humidity, nutrient content, and soil pH, in a much more efficient and real-time manner. These advanced technologies allow farmers to improve agricultural yields and reduce human effort, directly impacting energy and resource savings. For example, mobile devices and cloud-based services, along with the automation of agricultural operations, facilitate more efficient and precise decision-making regarding irrigation, fertilization, and harvesting [19]. A significant example of IoT application in agriculture is the use of automated farms, which employ wireless sensors to monitor essential parameters such as temperature, carbon dioxide levels, humidity, and light within greenhouses. These IoT sensor networks help farmers maintain optimal conditions for plant growth, ensuring more efficient resource management and maximizing crop yields. Additionally, GPS and ZigBee protocols are used to track critical agricultural parameters, thus helping farmers better manage water resources [34].

IoT not only enhances the monitoring of growing conditions but also helps in managing agricultural waste and reducing losses. Farmers can use sensors to monitor water and nutrient levels, preventing waste and improving resource efficiency. Additionally, the use of sensors to detect plant diseases helps reduce losses caused by such issues, contributing to more sustainable crop management. By enabling more efficient waste and resource management, IoT significantly contributes to enhancing agricultural sustainability [32, 33]

In waste management, IoT can help save resources, reduce transport times, and minimize visits to empty bins, thus avoiding fuel waste and reducing carbon emissions [46]. Smart waste management (SWM) involves the collection and analysis of data from sensors on smart bins and garbage trucks, optimization of collection routes, waste classification and segregation, as well as user support. SWM systems use connected smart devices that communicate through standard protocols, are AI-based, and are capable of measuring, processing, and transmitting information. These systems contribute to energy efficiency, environmental safety, reduced resource consumption, and improved citizens' quality of life [48]. In a study done by [46], two sub-models are presented that use IoT to manage waste more efficiently and sustainably. The first sub-model focuses on optimizing waste collection routes, while the second focuses on waste segregation into categories (paper, plastic, metal, glass, electronic waste, and wet waste), using IoT to monitor the amount of waste and direct vehicles to recovery centres. IoT systems enable the measurement, calculation, transmission, and processing of data to improve the efficiency and sustainability of waste management services. In smart cities, IoT and big data facilitate more efficient resource management, thereby enhancing the quality of life and promoting sustainable development [1]. The following figure illustrates how IoT can help in waste management, showing how smart technologies enable real-time monitoring, efficient waste collection, and resource optimization.

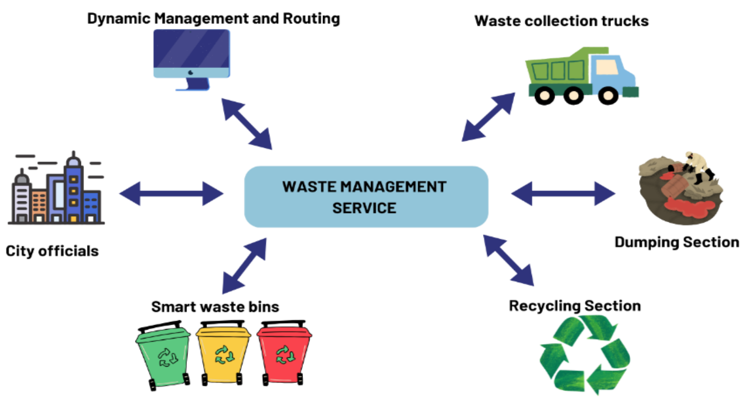

Figure 10. The way IoT can help in waste management (Adapted from [64])

Overall, IoT and AI technologies are essential in the development of a more sustainable, efficient, and productive agricultural system, enabling farmers to optimize plant growth conditions and improve resource management. These technologies have a positive impact on both agricultural production and environmental protection, thus contributing to a more sustainable agricultural future. Similarly, in waste management, IoT can help by providing real-time data from smart bins, optimizing collection routes, and reducing waste overflow, which improves efficiency, reduces operational costs, and minimizes environmental impact. By integrating IoT and AI, waste management systems can become more sustainable and effective, contributing to a cleaner and more efficient urban environment [26,32, 33].

6. Discussion

Efficient waste management technologies have been shown to play a key role in reducing environmental impacts and promoting sustainable development. Among the most efficient and economical solutions for organic waste management are waste-to-energy methods, such as composting and anaerobic digestion. Composting, in particular, has been shown to have a low initial cost, minimal equipment requirements, and the production of natural fertilisers, thereby reducing the need for chemicals in agriculture [58]. Anaerobic digestion, while more complex, is a cost-effective technology in the long term due to the production of biogas, which can be used for energy generation, and digestate, which can be used as a fertiliser. It is notable that anaerobic digestion offers high energy efficiency and low environmental impact [36]. In comparison, methods such as pyrolysis and Waste-to-Energy are also energy efficient, but require high investment and the management of complex technology. These methods are more suitable for large facilities or industries that can justify the costs through high volumes of waste processed [2].

The application of technologies incorporating artificial intelligence (AI) and the Internet of Things (IoT) has the potential to deliver effective solutions in the field of waste management. However, the effectiveness of these solutions is contingent on various factors, including the implementation methodology, scalability, and the context in which they are utilised. These technologies have the potential to address a number of challenges; however, it is imperative to consider their substantial financial implications, which need to be weighed against the long-term benefits they offer. Consequently, the selection of a waste management method should be based on a comprehensive analysis of specific factors, including the characteristics of the region, the nature of the waste generated, existing environmental conditions and long-term objectives. It is acknowledged that each region may possess distinct needs and resources, and that climatic conditions, extant infrastructure, and local environmental policy influence the selection of the most appropriate technology. The selection of a waste management method must be informed by the desired outcomes, which may include reduced environmental impact, cost efficiency, the creation of useful by-products or energy generation. The chosen method must be tailored to maximize benefits and minimize associated risks [26,32].

7. Conclusions

Agricultural waste represents a significant challenge for natural resource management and environmental protection, but also an opportunity to develop innovative solutions that support a sustainable agricultural system. By implementing recycling and recovery technologies, such as conversion into bioenergy, compost, and natural fertilizers, the agricultural sector can contribute to reducing the negative environmental impact and promoting a circular economy. It is essential that, as the need for resources grows, we develop and implement effective waste management strategies that not only minimize waste but also bring long-term economic and ecological benefits. In this context, a strong commitment to sustainability and innovation can transform agricultural waste from a problem into a valuable resource, thus contributing to a greener and more balanced future.

Conflicts of interest: The authors declare no conflict of interest.

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Article

INTELLIGENT MIXED CROP MONITORING AND PROTECTION SYSTEM (SIMPC): COMBINATION OF ADVANCED TECHNOLOGIES TO REDUCE DAMAGE CAUSED BY BIRDS

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Keywords: *artificial intelligence, destroyed crops, harmful birds, sustainable agriculture*

Abstract: *The protection of agricultural and horticultural crops against pests, including birds, represents a major challenge for the global agri-food sector. Birds, although essential for the ecosystem, can lead to significant economic losses by attacking plants, destroying crops and negatively influencing the quality of agricultural products. In this context, the implementation of intelligent protection systems becomes an urgent necessity, combining advanced technologies such as sensors, artificial intelligence (AI) and IoT (Internet of Things) to provide efficient and sustainable solutions. The research in this paper aimed to develop and evaluate an intelligent and sustainable system for the protection of crops against harmful birds. The specific objectives were: system design, integration of advanced technologies, performance testing, optimization of sustainability and identification of limitations for future improvements. Through an interdisciplinary approach, combining agronomy, engineering and environmental sciences, viable solutions for a modern and sustainable agriculture are outlined.*

1. Introduction

Agriculture and horticulture are essential sectors for ensuring food security and sustainable economic development. However, one of the major challenges' farmers face is protecting crops from harmful birds, which can cause significant production losses. Traditional control methods include the use of scares, protective nets or chemicals, but these are often ineffective or environmentally harmful.

In recent years, the development of smart technologies has provided innovative solutions for protecting crops from birds. Systems based on artificial intelligence (AI), sensors and acoustic or visual devices [1] allow for the detection and deterrence of birds in an automated manner, thus reducing manual intervention and the negative impact on the ecosystem. The use of drones, lasers and bird species recognition systems contribute to a more efficient and sustainable protection of agricultural and horticultural crops [2,3].

Smart systems for protecting crops from harmful birds include:

Acoustic systems include devices that emit high-frequency sounds or alarm calls specific to pest birds. Studies show that these systems can reduce the presence of birds by up to 60%, but their effectiveness decreases over time as birds become accustomed to the sounds [4].

Autonomous drones are used to patrol agricultural areas and to scare birds away through strategic flights. Drones equipped with sensors and AI algorithms allow for automatic identification and response to pest birds, with high effectiveness over large areas [5].

Laser-based systems use low-intensity lasers to deter birds and have been shown to be effective in numerous studies, with success rates of over 80% in preventing birds from accessing crops. These systems are particularly effective in the morning and evening, but may have limitations in bright light conditions [6,7]

Motion sensors and AI cameras allow for automatic bird detection and the activation of deterrent systems such as water jets, sounds or flashing lights. The integration of IoT sensors and artificial intelligence allows for the customization of the response depending on the type of bird and the level of threat [8].

Smart nets and adaptive physical barriers Unlike traditional nets, new smart materials are designed to be more resistant and easier to install. Some versions include sensors that detect the presence of birds and adjust the tension or structure of the net to prevent their access [9].

In conclusion, the efficiency of intelligent bird pest control systems varies depending on the technology used and the type of crop:

• Automated and AI-controlled lasers have demonstrated the highest efficiency, reaching up to 75% in the case of wheat and between 65-70% for other crops such as sunflower, raspberry and cherry [6,7,10,11,12].

• Autonomous robots have had moderate efficiency, ranging between 55-60%, making them a viable solution for vineyards, corn and orchards [13-17].

• Acoustic drones and AI sound devices have offered more modest results, with an efficiency of 50-55%, being more suitable for orchards and fruit crops [3, 5, 18,19].

• Smart nets integrated with IoT technology had an efficiency of approximately 50%, being successfully used for the protection of small fruits (strawberries, raspberries, cherries) [2].

• Drones equipped with LED projectors and reflective visual devices were less effective (40-45%), but can be used complementary to other methods [8,20].

Solutions based on automatic lasers and artificial intelligence are the most effective in crop protection, while acoustic, visual and IoT methods can be useful as complementary solutions. Choosing the right technology must take into account the type of crop and the specifics of the harmful birds in the area.

This article analyzes the latest technologies applied in this field, highlighting the advantages, limitations and development prospects of intelligent systems for protection against harmful birds. By integrating modern technologies, these systems not only minimize economic losses, but also reduce the negative impact on the environment, replacing traditional methods, which can be harmful to ecosystems.

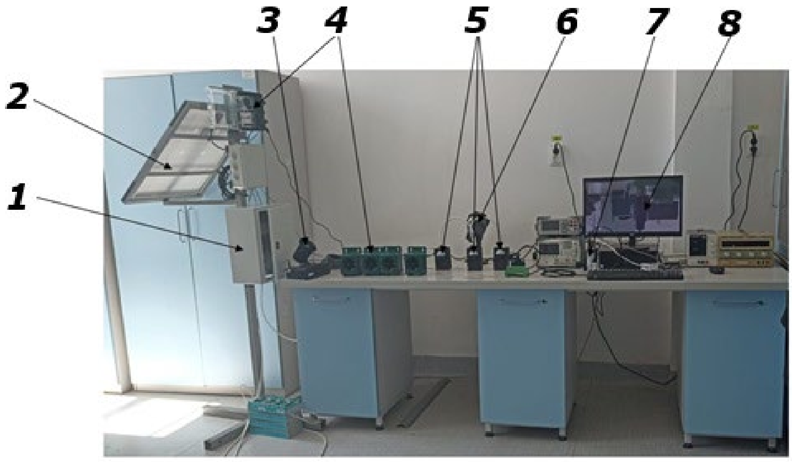
The aim of the research was to describe and evaluate an innovative system for protecting agricultural and horticultural crops against harmful birds, called SIMPC (Intelligent Mixed Crop Protection System). This system integrates advanced technologies, such as artificial intelligence (AI), lasers, acoustic devices and ultrasound, in a modular and sustainable architecture, powered by solar energy. The work aims to demonstrate the efficiency of the system in detecting and repelling birds, as well as to provide an ecological and economical alternative to traditional crop protection methods.

Objectives of the work were: (1) Development of the SIMPC System: Design and implementation of a mixed crop protection system, combining multiple repelling methods (laser, ultrasound, holographic tape) and using intelligent technologies (AI, IoT) for the detection and management of harmful birds. (2) Integration of Advanced Technologies: Implementation of an artificial intelligence algorithm (YOLOv8) for accurate bird detection and control of repelling devices. Use of a smart camera with deep learning capabilities for real-time monitoring of protected areas. (3) Testing and Performance Evaluation: Testing the system in real conditions (apple, plum and raspberry orchards) and evaluating the efficiency in detecting and repelling birds. Analysis of performance metrics (precision, recall, F1-score, mAP) and comparison with other existing systems. (4) Optimizing Sustainability: Implementing a solar power system to ensure energy autonomy and reduce operating costs. Minimizing environmental impact by avoiding harmful chemical or physical methods. (5) Identifying Limitations and Improvement Proposals: Analyzing system limitations (costs, bird adaptation, false negatives) and proposing solutions to optimize performance. Suggesting future research directions, including expanding tests to other types of crops and environmental conditions. (6) Promoting Innovation in Agriculture: Demonstrating the potential of the SIMPC system as an innovative solution for farmers, contributing to increasing productivity and reducing crop losses

2. Materials and methods

2.1. Description of the SIMPC System

The SIMPC system (Intelligent mixed Crop Monitoring and Protection System), figure 1, is an integrated system designed to detect and repel birds that can damage agricultural crops.



1 – command and control panel; 2 – solar power system; 3 – sonic generator; 4 – ultrasonic and sonic generator; 5 – motion sensors; 6 – laser system; 7 – smart camera; 8 - monitor

Figure 1. Intelligent mixed crop monitoring and protection system – SIMPC

The system architecture is modular and consists of three main components:

1. Power Module:

- Solar Panels: Provides power to the entire system, providing energy autonomy.
- Batteries: Stores the energy generated by the solar panels to ensure continuous operation of the system, including during periods without sunlight.

2. Detection Module:

- Smart Camera, figure 2, (NVIDIA Jetson Xavier NX, 2M resolution): Uses advanced image processing technologies to detect the presence of birds.
- Motion Sensors, figure 3, are complements the smart camera, detecting movement in the monitored area.

Figure 2. Smart camera

Figure 3. Motion sensors

3. Repellent Module:

- Laser system (figure 4): Emits low-power green and red laser beams (class 3R) to repel birds without harming them.
- Sound and Ultrasound Generator (figure 5): Emits sounds and ultrasounds at specific frequencies (15-25 kHz), acoustic power (95-102 dB), to repel birds.

- Holographic Tape (figure 6): Reflects light and creates visual effects that repel birds.
- Kite (figure 7): Used as an additional method of repelling, the kite is designed to scare birds through its movement.

Figure 4. Laser system

Figure 5. Sound and ultrasound generator

Figure 6. Holographic tape

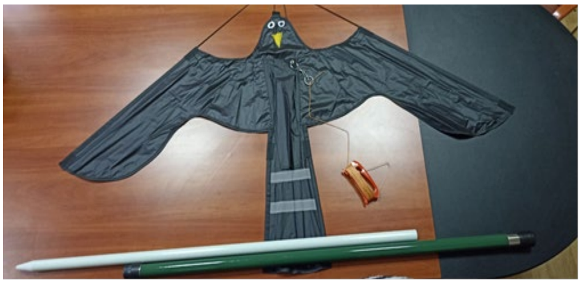


Figure 7. Kite

The SIMPC system uses a dual control architecture to ensure maximum redundancy and efficiency:

❖ Architecture 1: Based on Smart Camera and Laser. This architecture relies on data received from the smart camera to activate the laser and repel birds. The camera detects the presence of birds and sends a signal to the rappeler module to activate the laser.

❖ Architecture 2: Based on Motion Sensors and Sound Generator. This architecture uses motion sensors to detect the presence of birds and activates the sound generator to repel them. It is used as an alternative or complement to architecture 1.

2.2. SIMPC Operating Algorithm

For the operating algorithm of SIMPC, an image processing or detection algorithm, a simplified scheme is shown in the figure 8.

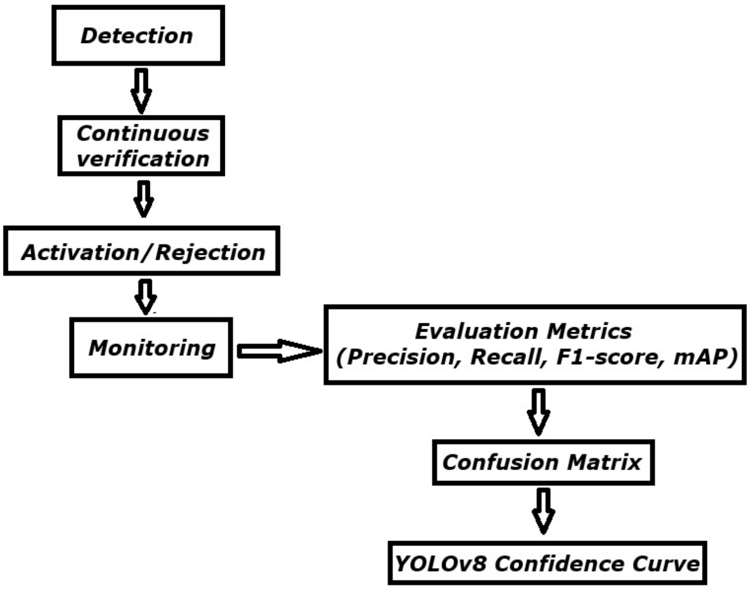


Figure 8. Visual diagram of the SIMPC operating algorithm

This diagram represents the essential steps of the SIMPC algorithm, starting with the initial detection, continuing with the verification and activation or rejection, and ending with the monitoring and evaluation using metrics such as precision, recall, F1-score and mAP.

The confusion matrix and confidence curve for YOLOv8 are related to the evaluation of the algorithm's performance and are used to adjust and improve the detections.

The advanced features of SIMPC are: both the random mode to prevent bird habituation, the system activates the repellers randomly and the adaptability, which refers to the fact that the algorithm adjusts itself according to the behavior of the birds and the environmental conditions.

2.3. YOLOv8 Model Training

A detailed description of the training process of the YOLOv8 model for detecting pest birds (crows), along with a schematic representation of the training flow, is presented in figure 9.

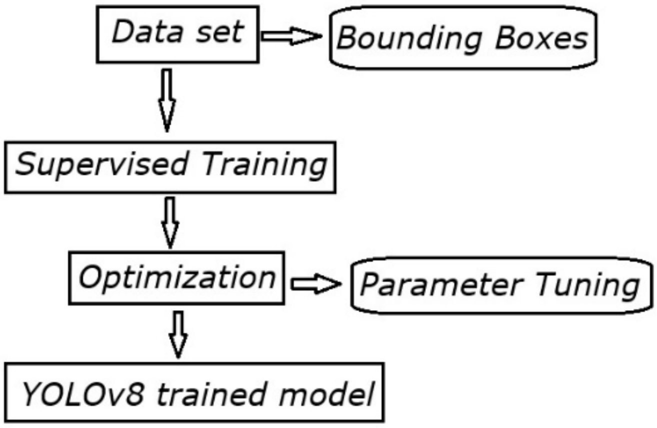


Figure 9. Schematic of the YOLOv8 model training process

This is the general process for training a YOLOv8 model for detecting pest birds, such as crows, in images.

The Dataset contains images of pest birds (e.g., crows) in various poses (flight, landing, on the ground, etc.). The images are labeled with bounding boxes that indicate the position of the birds in each image.

The YOLOv8 model is trained using labeled images, learning to identify and locate birds in the images, followed by automatic labeling with the coordinates of the bounding boxes that mark the birds, then the loss function calculates the difference between the model's predictions and the actual labels.

Optimization techniques are used to adjust the model parameters, such as learning rates and network weights. The model is optimized to maximize precision (the proportion of correct detections out of all detections made by the model) and recall (the proportion of correct detections out of all relevant instances). This may include adjustments to reduce false positive and false negative rates.

In this stage, the YOLOv8 model learns to differentiate pest birds from other objects, using the bounding box labels as a guide. It can also learn to recognize various bird poses.

3. Results and discussion

3.1. Preliminary testing of the intelligent mixed system for protecting agricultural crops from bird attacks

Preliminary test results in laboratory conditions, i.e. a controlled environment, to validate the functionality of the system used simulated data sets, namely images and simulated scenarios with harmful birds (e.g. crows), and to verify the performance of the YOLOv8 model, testing in real conditions follows, i.e. in the field and orchards.

The preliminary results of the SIMPC are shown in the table 1:

Table 1

Preliminary results of SIMPC

Performance Metrics	Value obtained	Interpretation
Precision	0.55925 – 55.93%	The model's detections were correct.
Recall	0.52527 – 52.53%	The real birds were correctly detected
Scor F1	0.59204	The balance between precision and recall
mAP (mean Average Precision)	0.62892	Indicates the overall performance of the model in detecting birds

The preliminary results presented in the table 1 show that the system has demonstrated efficiency in reducing bird damage, which indicates that this model can be practically applied.

3.2. Training results:

Matricea de Confuzie:

-True Positive (TP): 25 – Birds detected correctly.

-False Negative (FN): 4 – Birds not detected by the model.

The confusion matrix helps to understand the behavior of the model, clearly indicating how many objects were correctly detected and how many were missed.

The Confidence Curve shows the performance of the model for different confidence thresholds. For example, if a higher threshold is set, the model may be more accurate, but may miss more objects (resulting in lower recall). If a lower threshold is set, the model may detect more birds (higher recall), but at the risk of generating more false positives (lower precision).

In the case of this model, there is a trade-off between precision and recall. However, the values for both metrics suggest that improvements are needed, especially to reduce the number of false negatives (FN) and to improve the accuracy in correct detections. These results suggest a working model, but that can benefit from improvements, for example, by adjusting the confidence thresholds, augmenting the datasets, or refining the optimization algorithm.

4. Discussions

The system's contribution to crop protection against harmful birds provides an innovative and adaptable solution for crop protection and reduces dependence on environmentally harmful chemical or physical methods.

Future research directions can be based on both expanding the tests to many crops (orchards, vineyards, field crops, etc.) and under diverse environmental conditions, as well as optimizing the AI algorithm to reduce false negatives.

The advantages of SIMPC are: (1) The combination of repelling methods (laser, ultrasound, holographic tape); (2) It allows the use of both smart camera and motion sensors, providing redundancy that increases the reliability of the system. (3) The flexibility of the dual architecture; (4) Sustainability due to the power supply with solar panels.

The limitations of SIMPC are: (1) High initial costs; (2) The need to test on several types of crops (cereals, sunflowers, etc.) and in various environmental conditions (rainy weather, snow, etc.); (3) The system is more complex than other existing solutions, which may require training for farmers or technicians; (4) Although the system uses various methods, there is a risk that birds adapt over time to certain stimuli (for example, if the laser is used too often); (5) The YOLOv8 algorithm has a good accuracy (0.55925), but can be improved to reduce the number of false negatives (4 cases in tests).

Suggestions for improving SIMPC include: expanding the tests, optimizing the AI algorithm, reducing costs, and integrating with other technologies: such as adding drones to extend the system's coverage to large fields.

The SIMPC system is innovative and promising due to the combination of technologies (AI, laser, ultrasound, solar energy) and the flexibility offered by the dual architecture. It is more versatile than most existing systems, which focus on a single rejection method. However, testing on more types of crops and improving the AI algorithm is necessary to maximize efficiency.

5. Conclusions

General conclusions on crop protection using IoT and AI:

• Smart agriculture technologies are essential for increasing productivity and sustainability in agriculture.

• IoT provides a robust platform for integrated risk management in agriculture, including bird protection.

• Integrated approaches, combined with modern technologies, are the key to sustainable agriculture.

• AI has immense potential in optimizing crop protection, providing personalized and adaptable solutions.

• Advanced technologies, such as drones, represent the future of crop protection against birds.

The specific conclusions of SIMPC are:

• Summary of results: SIMPC is an effective and versatile system for crop protection against pest birds.

• Practical implications: It can be implemented in agricultural farms to reduce crop losses.

• Contribution to the field: Introduces a multi-technological and sustainable approach to pest bird management.

• Recommendations: Large-scale testing and cost optimization for wider adoption.

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Review

MODERN PEA SOWING TECHNOLOGIES: EFFICIENCY, PRECISION, AND SUSTAINABILITY IN CONTEMPORARY AGRICULTURE

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Keywords: *seeders; efficiency; sustainability; precision*

Abstract: The protein content and quality of pea seeds are strongly influenced by cultivation practices and processing methods. Soil fertility, stress conditions, and harvest timing affect protein synthesis and amino acid profiles. Post-harvest treatments can enhance or degrade protein digestibility and nutritional value. Optimized agronomic and processing strategies are essential to ensure high-quality pea protein for human consumption. Pea sowing represents a crucial stage in the agricultural process, and the use of modern sowing technologies has brought significant improvements in the efficiency and sustainability of this process. Seeders, equipped with advanced depth and seed distribution control systems, enable uniform and efficient sowing, reducing resource waste. These modern technologies not only support more efficient resource management but also contribute to environmental protection by reducing the need for chemical treatments and improving soil structure. Additionally, the sowing process helps combat pests and diseases by ensuring even plant distribution, making them more resilient. Although implementing these technologies may involve high initial costs, the long-term economic and ecological benefits make them a valuable investment in agriculture. This chapter explores the impact of modern seeders on contemporary agriculture, highlighting the advantages and challenges associated with their use.

1. Introduction

Pea seeds (Pisum sativum) represent a highly valuable component of the human diet due to their rich nutritional profile. They are an excellent source of plant-based protein, containing approximately 23–25% protein by dry weight, with a favorable amino acid composition rich in lysine but limited in methionine, making them complementary to cereal grains in mixed diets. The high protein digestibility (over 85%) enhances their nutritional efficiency [1]. In addition to protein, pea seeds are a good source of complex carbohydrates, primarily starch and dietary fiber, contributing to glycemic regulation and satiety. Total dietary fiber ranges from 8 to 11 g/100 g dry matter, including both soluble fibers, which support blood glucose and cholesterol control, and insoluble fibers, which promote digestive health. The seeds are low in fat (typically <2%), and the lipid fraction is predominantly unsaturated. Peas also provide a range of micronutrients, including iron, phosphorus, potassium, magnesium, zinc, and B vitamins such as folate and thiamine, contributing to metabolic function and cellular health. Their low glycemic index and absence of cholesterol make them suitable for diabetic and cardiovascular health-oriented diets. Furthermore, peas are free of gluten and represent a hypoallergenic protein source, increasingly used in functional foods and plant-based formulations. These attributes underscore the role of pea seeds as a sustainable and nutritionally dense ingredient in diverse human diets.

The quality of pea seeds for human consumption is closely linked to agronomic practices throughout the cultivation cycle. Factors such as seed selection, sowing time, soil fertility, irrigation management, and pest control directly affect nutrient accumulation, seed composition, and the presence of anti-nutritional factors. Optimal planting density and timely sowing ensure uniform growth and efficient nutrient uptake, which enhances protein synthesis and starch deposition. Soil quality and the availability of essential macro- and micronutrients—particularly nitrogen, phosphorus, and zinc—play critical roles in determining protein content and amino acid balance [2]. The application of biofertilizers and integrated nutrient management can further improve seed nutritional density while maintaining environmental sustainability. Crop management practices such as weed control, disease prevention, and use of biostimulants contribute to healthier plants, reducing physiological stress that could compromise seed quality. Excessive use of chemical inputs, on the other hand, can lead to pesticide residues or reduced soil microbial activity, negatively impacting food safety and nutrient bioavailability. Harvesting at optimal maturity is essential to ensure proper seed hardness, protein concentration, and storage quality. Post-harvest handling, including drying and storage, also influences the preservation of vitamins and prevention of fungal contamination. In sum, sustainable and precise crop management practices are essential to maximize both the yield and the nutritional quality of pea seeds intended for food applications [3].

The protein content and quality of pea seeds are determined not only by genetic factors but also by environmental conditions and agricultural management during cultivation. Soil fertility—particularly nitrogen availability—directly influences the biosynthesis of storage proteins such as legumin and vicilin. Practices that enhance soil health, such as crop rotation with legumes, use of organic fertilizers, and microbial inoculants (e.g., Rhizobium spp.), can improve nitrogen fixation and protein yield. Abiotic stresses such as drought, excessive heat, or nutrient deficiencies during flowering and seed development can lead to reduced protein accumulation and altered amino acid profiles. Harvest timing is also critical: premature or delayed harvesting may reduce protein concentration or promote degradation of functional proteins [4].

Post-harvest processing—especially drying, dehulling, and thermal treatments—further affects protein quality. Excessive heat during drying or cooking can cause denaturation of proteins, reducing solubility and digestibility, while moderate thermal treatment may improve the nutritional value by inactivating anti-nutritional factors like trypsin inhibitors. Milling and fractionation can concentrate protein but may result in the loss of certain amino acids or micronutrients if not carefully controlled. Innovative processing techniques, such as air classification, fermentation, or enzymatic hydrolysis, are increasingly used to enhance protein bioavailability and functional properties for use in plant-based food formulations. Overall, the preservation of high protein content and quality in peas requires integrated attention to cultivation, harvesting, and processing parameters tailored for food-grade applications [5].

Pea (fig.1) is a widely cultivated legume crop, known not only for its nutritional value but also for its agronomic benefits. One of its major advantages lies in its ability to enrich the soil with nitrogen due to the presence of nodule-forming, nitrogen-fixing bacteria on its roots, which reduces the need for synthetic nitrogen fertilizers [1].

Fig. 1 - Pea (Pisum sativum L.) [2]

Population statistics indicate a substantial rise in the global population, projected to reach 10 billion by 2050. As a result, the global challenges of energy and water scarcity, food security, and climate change are expected to intensify [3,4,5]. In the context of modern agriculture, food systems exert increasing pressure on ecosystems [6]. Balancing ecosystem protection with the need to provide sustainable nutrition for the global population has become a critical concern in recent years [7]. Over the past decades, there has been a growing global trend towards the production and consumption of environmentally friendly food, cultivated in clean areas without the use of mineral fertilizers, pesticides, or other synthetic inputs [8,9].

Automation and software programs are transforming legume production, increasing efficiency, precision, and sustainability. Advanced technologies such as sensors, IoT devices, and autonomous machinery help monitor and manage every stage of crop development. Soil sensors provide real-time data on moisture, temperature, and nutrient levels, enabling precise irrigation and fertilization. Drones equipped with multispectral cameras survey fields, identifying stressed areas and enabling targeted interventions.

Automated planters and harvesters reduce labor demands and ensure uniform crop establishment and collection. GPS-guided tractors allow for precision field operations, reducing overlap and optimizing resource use. Variable rate technology (VRT) adjusts input application rates according to field variability, improving productivity and reducing environmental impact.

Software platforms integrate data from multiple sources, offering farmers centralized dashboards to monitor operations and make informed decisions. Farm management systems track planting schedules, input use, weather forecasts, and yield predictions. Decision support systems use AI algorithms to recommend pest control actions, planting dates, or optimal harvest windows based on predictive models.

Greenhouse vegetable production benefits from environmental control software, which automates temperature, humidity, lighting, and CO_2 levels. In hydroponics and aquaponics, automation ensures balanced nutrient delivery and water quality. Robotics are increasingly used for transplanting, weeding, and selective harvesting, especially in high-labor-intensity crops.

Machine learning models process data from previous seasons to improve future planning and risk assessment. Cloud-based platforms enable remote monitoring and collaboration among producers, agronomists, and suppliers.

The integration of automation and software programs not only increases operational efficiency but also supports sustainable practices by minimizing waste and optimizing inputs. As digital agriculture evolves, legume production is becoming more resilient, profitable, and climate-smart.

Fig. 2 - Start Analyzing & Visualizing your data with HortControl Software [10]

HortControl is the central software to setup your experiments and to store and manage data locally on a site. Within seconds after the scan, the plant parameters sets can be visualized and analyzed with the HortControl tool box [10].

The production of high-quality agricultural products remains a top priority within the crop industry [11,12]. At the same time, preserving soil fertility, ensuring ecological purity, and promoting resource conservation are equally important goals [13,14,15]. Achieving these objectives requires the adoption of adaptive cropping systems [16], which rely on the renewable resources of biological communities—such as plant and microbial systems—to supply essential nutrients to plants and enhance their stress resilience [17]. In this context, legume agrocenoses formed in symbiosis with nodule bacteria represent a fundamental element of organic farming, as these systems exhibit mutual compatibility and functional complementarity.

Pea is cultivated for both green pods and mature seeds [18]. The pods are slightly aromatic, sweet, and crispy, and notably lack pod parchment [19]. In India, for instance, pea is typically grown as a winter vegetable in the northern plains and as a summer vegetable in hilly regions. It is commonly consumed fresh, canned, processed, or dehydrated. India remains the largest producer and importer of leguminous crops [20].

From a nutritional standpoint, pea is an excellent food for human consumption, whether used as a vegetable or in soups. The immature seeds found in green pods are especially popular for these uses. Additionally, pea herbage harvested shortly after pod picking serves as a valuable green fodder for livestock [21].

Field peas are among the leading grain legumes for both food and forage due to their rich and balanced amino acid profile. Pea seeds contain approximately 22–24% total protein, 1.5% fat, 55% nitrogen-free extractives, and 6–8% crude fiber. They are also a vital source of lysine—an essential amino acid—present in concentrations 3–4 times higher per kilogram than in cereal grains [22,23].

Pea is cultivated across nearly all regions of the world and plays a significant role in the human diet [24]. It holds particular importance in vegetarian and vegan nutrition, where its high protein content helps individuals meet their dietary protein requirements in the absence of meat and dairy products [25,26]. Sowing date and cultivar selection are key management strategies for optimizing both seed yield and protein content [27]. Numerous studies [28,29] have reported that early sowing increases yield, while delayed sowing leads to reductions.

In recent years, catch crops have gained attention due to their positive impact on soil health. They improve the physical and biological properties of soil [30,31] and reduce the risk of eutrophication caused by nutrient leaching [32,33]. Within cropping systems dominated by cereals, selecting appropriate species for catch crops is essential. Legume crops are particularly desirable in this role due to their beneficial effects on soil chemistry and structure [34,35], though they do require early sowing to be effective [36].

2. Materials and methods

Sowing peas is a fundamental task in the cultivation technology of this vegetable, having a significant impact on the uniformity of germination, plant density, and, ultimately, on the yield. Pea (Pisum sativum L.) is a leguminous plant distinguished by its relatively large, spherical, and fragile seeds, characteristics that require the use of specially designed sowing machines to prevent seed damage.

Regarding the sowing period, it must be carefully chosen to match the specific climatic and moisture conditions of each region. Sowing is usually done in early spring, between March and April, when the soil reaches a temperature of at least 4–5°C. Early sowing is essential for uniform crop development, and delaying sowing can lead to reduced yields and the emergence of pest risks.

For sowing peas, mechanical seeders are generally used, which allow for the uniform distribution of seeds. These seeders are equipped with dosing systems that regulate the amount of seed, considering the specific characteristics of pea seeds. Typically, a sowing depth of 4–6 cm is recommended, ensuring good root development and uniform germination.

The seeders are equipped with opener discs that allow for easy penetration into the soil, even in high humidity conditions. These seeders are extremely useful for working in heavy soils or soils with plant residues, which can complicate sowing.

Regarding sowing density, it is adjusted based on the purpose of the crop – for green pod production or for dry bean production. In general, seed rates range between 170–250 kg/ha, depending on the type of pea and soil conditions. The final plant density usually reaches approximately 90–110 plants per square meter. For sowing aimed at green pod production, narrower rows are recommended to ensure quick soil coverage and reduce weed growth.

Another important aspect in pea sowing technology is the precise monitoring of the distance between seeds. Distribution errors can severely affect the uniformity of the crop and lead to a low yield. Modern precision seeders are equipped with monitoring sensors that constantly control the seed flow and adjust the dosing to ensure uniform distribution. This allows for reducing the error to below 10%, resulting in uniform germination and a well-established crop.

Modern seeders are equipped with ISOBUS and GPS control systems, which allow precise operation of the machinery, even in large farms. These technologies enable users to control sowing speed, record accurate data on operations performed, and adjust sowing parameters in real-time, significantly improving sowing efficiency.

Regarding sowing speed, it plays a crucial role in achieving maximum yield. Typically, sowing is done at a speed of about 4–7 km/h. Higher speeds can lead to uneven seed distribution and seed damage, while speeds that are too low can extend working time and affect sowing quality. Modern seeders are equipped with damping systems that help maintain the stability of the machinery even at high speeds.

As for soil preparation before sowing, it is important for the soil to be properly prepared. A preliminary pass with a combiner or adjustable-tooth harrow is recommended to break up solid soil structures and create a fine seedbed.

Finally, choosing the right seeder is not just about technical specifications but also the cost-benefit ratio. Modern seeders, equipped with state-of-the-art technologies, may initially seem expensive, but the advantages they bring—such as reduced seed loss, increased crop uniformity, and higher work efficiency—justify the investment, especially for medium and large farms. These machines allow for optimized fuel consumption and reduce the number of passes across the field, which lowers operating costs and increases long-term profitability.

3. Results

This chapter presents modern seeding machine models used in agricultural crop sowing, with a focus on their ability to successfully incorporate pea seeds. While these machines are primarily designed for cereal crops, their technical configurations—such as precise depth control, advanced seed distribution systems, and the ability to sow seeds of various sizes—make them suitable for sowing legumes, including peas.

Peas are typically sown in rows with a spacing of 12–15 cm, and the seeders discussed below, thanks to their versatility and adjustable technical parameters (such as pressure on the coulters, seed dosage, disc diameter, etc.), can ensure uniform seed distribution and consistent sowing depth. This results in optimal conditions for germination and crop development.

Therefore, the seeders presented in this chapter—METRO MEGA by Maschio Gaspardo, SUP 400 DIAMANT by Mecanica Ceahlău, and PREMIA 9000 TRC by Kuhn—can be successfully used for pea cultivation, offering efficient and reliable solutions for farms aiming to achieve uniform emergence and high yields.

3.1. METRO MEGA Seeder – MASCHIO GASPARDO

The Italian company Maschio Gaspardo manufactures the METRO MEGA seeder (fig. 3), a high-capacity agricultural equipment created by combining four SC MARIA seeder modules that operate synchronously in parallel. This configuration is made possible by a towed frame with foldable sides, which reduces the transport width to just 6 meters, thus facilitating the movement of the machinery on public roads.

Fig. 3 - METRO MEGA Seeder [37]

The seeder retains the functional characteristics of the models it is derived from, including:

- Mechanical transmission with three cams in an oil bath,
- Compartmented hopper for the simultaneous distribution of seeds and fertilizers,
- Double disc furrows, equipped with adjustable compression springs.

Technical specifications – METRO MEGA:

- Working width: 12 m
- Number of rows: 88
- Row spacing: 13.6 cm
- Seed hopper capacity: 1,320 l
- Fertilizer tank capacity: 1,080 l
- Transport width: 6 m
- Required power: ≥ 240 HP
- Weight: ≥ 9,200 kg

3.2. SUP 400 DIAMANT Seeder – MECANICA CEAHLĂU

Produced by the Romanian company Mecanica Ceahlău, the SUP DIAMANT range of cereal seeders is designed for row sowing and includes two models with working widths of 3 m and 4 m. These seeders are equipped with a Norton gearbox featuring 72 speeds, allowing for fine adjustment of seed rates. The triple distributor enables the application of very small seeds (e.g., rapeseed, clover, alfalfa) at rates as low as 2 kg/ha.

The SUP 400 DIAMANT seeder (fig. 4) offers multiple advantages:

- Adjustable double-disc coulters for depths up to 8 cm
- Large hopper capacity
- Telescopic markers with spherical discs
- Packing wheels included as standard
- Rapid switch between small and standard seed types
- Triple distributor for a wide range of crops

Optionally, it can be equipped with: covering tines, packing chains, systems for shutting off two or three rows, and simultaneous fertilizer application.

Fig. 4 – SUP 400 DIAMANT Seeder [38]

Technical Specifications – SUP 400 DIAMANT:

- Equipment type: mounted, category II ISO
- Required power: 120–140 HP
- Working width: 4 m
- Number of rows: 31
- Row spacing: 13 cm

- Seed distribution: triple spiked roller
- Seeding rate adjustment: 72-speed gearbox
- Seed hopper capacity: 1,260 L
- Coulter type: double disc, 370 mm diameter
- Productivity: 1.4–2.8 ha/h
- Working speed: 5–10 km/h
- Dimensions (L x W x H): 2.46 x 4.6 x 1.62 m
- Weight: 2,100 kg

3.3. PREMIA 9000 TRC Seeder – KUHN (France)

The French company Kuhn manufactures the PREMIA 9000 TRC seeder (fig. 5), a mechanical model designed for large farms using medium-capacity tractors. It is a towed, foldable seeder without a soil preparation unit, with a working width of 9 meters and a transport width of only 3.5 meters.

Fig. 5 - The mechanical seed drill PREMIA 9000 TRC [39]

It is a combined seeder for both seeds and fertilizer, distributed simultaneously in the same row (60% of the hopper for seeds, 40% for fertilizer). The machine is equipped with 4 HELICA dosing units, allowing distributions between 1.5 and 300 kg/ha, for all types and sizes of seeds.

The dosing is ensured by helicoidal rollers, mechanically driven by lateral drive wheels and cam variators, maintaining a constant flow, independent of the travel speed. The components are mostly made of stainless steel for an extended service life.

4. Discussions

Sowing peas is a crucial step in the cultivation technology of this vegetable, and choosing the right technologies for sowing plays a decisive role in the success of the crop. Over the decades, the continuous development of sowing machinery has led to the implementation of increasingly precise solutions, which not only improve yields but also contribute to more sustainable resource management.

Modern sowing machines, such as precision seeders equipped with advanced mechanical systems, allow for uniform seed distribution, which is essential for achieving a uniform crop. Compared to traditional seeders, these technologies are much more efficient, reducing the risks of seed distribution errors and providing much stricter control over the sowing depth.

An important aspect to mention is the impact that precision sowing has on economic and ecological efficiency. Modern seeders, equipped with GPS and ISOBUS technologies, enable precise operation and the recording of relevant data for each field lot. This not only optimizes fuel consumption and reduces operating costs but also allows for better monitoring of sowing parameters. This efficiency translates into resource savings, including reduced seed and fertilizer consumption.

Additionally, the implementation of these technologies aligns with the general trend in agriculture to reduce environmental impact. Modern seeders can precisely adjust the amount of seeds distributed, reducing waste and ensuring optimal plant density. This can contribute to improving soil health and more efficient nutrient use. Furthermore, the fact that these machines are more efficient in soil processing, especially in humid conditions or heavy soils, helps reduce erosion and maintain soil structure in the long term.

At the same time, precision sowing helps address another important aspect of modern agriculture: pest and disease management. A uniform sowing reduces the risk of plant overcrowding, which can attract pests or promote disease development. Moreover, by better controlling plant density, the need for chemical treatments can be reduced, thus supporting organic farming and minimizing the impact on biodiversity.

Another relevant aspect concerns the adaptability of modern seeders to different soil and climate conditions. Although sowing technologies are highly advanced, it is important for farmers to understand and choose the right type of seeder based on the specifics of the land they are working with. For example, seeders that allow for depth adjustment are essential in areas with denser soils or plant residues. Furthermore, these seeders can be configured to sow more sensitive crops, such as peas, which require gentle handling of the seeds.

Regarding the size of the machinery, large-scale seeders, such as the METRO MEGA or DIAMANT models, enable fast and efficient operation on large farms, significantly impacting productivity per unit area. However, the initial costs of such equipment can be high, and the purchase decision must be made based on the size of the farm and its specific needs. In this regard, a careful cost-benefit analysis is essential, considering long-term savings in fuel, maintenance, and seed conservation.

Sowing peas with modern technologies, such as precision seeders, plays a fundamental role in today's agriculture, contributing both to improved yields and supporting ecological and sustainable practices. The efficiency of these machines, combined with the responsible use of resources and their adaptability to varying field conditions, makes these technologies a valuable investment for farmers worldwide. However, to maximize the benefits of these technologies, it is important for farmers to be educated and have access to relevant information that enables them to make informed decisions when selecting the right equipment and to understand their long-term impact on the environment and the economy.

5. Conclusions

Modern seeding technologies have brought a significant leap in the efficiency and sustainability of agriculture, and pea seeding is no exception. The use of seeders equipped with advanced seed dosing systems, seeding depth control, and GPS monitoring allows for uniform and precise sowing, with a direct impact on the growth and development of the crop. This leads to higher and more consistent yields, reduced seed loss, and more efficient resource management, particularly fuel and fertilizers.

Furthermore, modern seeders reduce the risks associated with seed damage, providing a constant and uniform sowing flow. These technologies also support ecology by limiting the use of chemical inputs and improving soil structure. The implementation of such technological solutions contributes to healthier and more resilient crops, which, ultimately, supports the increase in agricultural productivity and sustainability.

However, high initial costs and the need to adapt the technology to the specific conditions of each farm remain significant challenges for the widespread adoption of precision seeders. Nevertheless, the long-term benefits — resource savings, higher yields, and environmental protection — make these technologies a valuable investment for medium and large farms.

In conclusion, pea sowing using modern seeders represents an important direction for the future of agriculture, providing innovative solutions that improve not only production efficiency but also the long-term sustainability of agricultural activities. The adoption of these technologies will play a crucial role in achieving global objectives related to food security, environmental protection, and responsible resource use.

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Article

DEVELOPMENT OF AN INTEGRATED DRONE-BASED SYSTEM FOR COMBATING WILDLIFE TO FIELD CROPS

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Abstract: Wildlife damage poses a persistent threat to agricultural productivity, particularly in field crops such as maize, wheat, sunflower, and rapeseed. Species like wild boars, deer, hares, and birds can cause extensive losses by feeding, trampling, or uprooting crops. Traditional control methods—such as fencing, scarecrows, chemical repellents, or manual patrols—often prove insufficient, labor-intensive, or environmentally unsustainable. In this context, drones offer an innovative, eco-friendly, and cost-effective approach to wildlife monitoring and deterrence. This paper explores how drones can be used to detect wildlife presence through thermal and RGB imaging, identify intrusion patterns, and support real-time response strategies. Additionally, drones equipped with audio and visual deterrents can actively scare away animals, especially in vulnerable field zones. The integration of drones with IoT systems and AI-based recognition software enhances their effectiveness, enabling autonomous, targeted, and data-driven field protection. Despite certain challenges—such as battery limitations, regulatory constraints, and reduced effectiveness over time—drones represent a valuable tool in the transition toward sustainable agriculture. Their use can significantly reduce crop losses, minimize chemical usage, and improve farm resilience in wildlife-affected areas. This paper highlights key applications, limitations, and future directions for drone-based wildlife management in field crop farming.

1. Introduction

The rapid advancement of drone technology over the past decade has significantly transformed wildlife monitoring, ecological research, and conservation practices. Unmanned Aerial Vehicles (UAVs) equipped with thermal, multispectral, or high-resolution RGB cameras have become indispensable tools for collecting real-time, high-resolution data on wildlife distribution, behavior, and population dynamics [1, 10, 14]. These platforms offer a cost-effective, scalable, and less invasive alternative to traditional field-based methods.

Among the most promising applications is the detection and tracking of animals using their thermal signatures [1, 10], as well as real-time species identification through visual data processed with artificial intelligence and machine learning algorithms [5, 6, 12]. Technologies such as YOLOv5, SAHI, and GIS-based classification systems have been successfully used to detect and classify species even in challenging environmental conditions, offering direct benefits for biodiversity monitoring and agricultural conflict management [5, 6, 12].

In agriculture, wildlife-related crop damage—caused by species such as wild boars, roe deer, hares, and birds—is a widespread problem, particularly in forest-adjacent or poorly fenced regions. Recent studies indicate that drones can be used not only for early detection but also for active deterrence, using visual or acoustic stimuli to prevent wildlife intrusions [2, 4, 20]. Furthermore, new research highlights the use of drones in **hazing techniques**—non-lethal methods to deter predators such as wolves from preying on livestock. For example, Ranglack et al. [22] demonstrate that drones can be a practical hazing tool, especially when combined with sound or movement stimuli, showing potential in reducing human-wildlife conflict in grazing systems.

Moreover, drones enable real-time analysis of animal movement patterns and adaptation of deterrence strategies, reducing the reliance on expensive and labor-intensive interventions. Systematic drone-based habitat monitoring provides essential insights into wildlife ecology and conservation needs. UAVs have been successfully used to track bird colonies affected by disease [11], observe marine mammal behavior [16], and estimate the size of partially submerged reptiles such as crocodilians [9]. Additionally, drones have demonstrated high accuracy in estimating wildlife populations such as manatees, hares, and roe deer, offering results comparable to or surpassing traditional survey methods [3, 17].

More recently, integrated monitoring systems that combine drones with CubeSats and high-altitude pseudo-satellites (HAPS) have emerged, expanding the capacity for long-range, wide-area, and inaccessible region surveillance [8, 19]. These multi-platform solutions enable synchronized, multifactorial data collection on wildlife distribution, habitat changes, and human-wildlife interactions at unprecedented scales [7, 19, 21].

However, the use of drones in natural environments also raises important concerns. Studies have shown that certain drone flight patterns—especially those involving low altitudes or high frequency—can induce stress responses or behavioral changes in wildlife, potentially disrupting feeding, breeding, or movement routines [2, 4, 18]. Consequently, flight path design, drone type, and timing must be carefully calibrated to minimize disturbance and ensure ethical monitoring practices [1, 15].

In conclusion, drone-based wildlife monitoring offers significant opportunities for ecological research, biodiversity conservation, and sustainable agricultural management. With continued advancements in computer vision, sensor integration, and autonomous mission planning, drones are becoming essential tools for bridging the gap between technological innovation and ecological responsibility. As these technologies evolve, their role in supporting efficient and adaptive wildlife management strategies will only grow stronger [3, 8, 21, 22].

Wildlife can have a significant impact on field crops, either through direct damage or indirectly by disrupting the agricultural ecosystem. Below are some of the most common wild animals that cause damage to field crops in Romania and similar regions, along with the types of associated damage:

1. Wild Boar (Sus scrofa)

- Damage: rooting the soil, consuming maize, wheat, potatoes, and other crops; complete destruction of crop rows.
- Critical periods: autumn (during maize ripening), but also spring, when crops are young.

2. Roe Deer (Capreolus capreolus)

- Damage: feeds on young plants, especially sunflower, soybean, rapeseed, and grapevine crops.
- Critical periods: spring and early summer.

3. Large Cervids (Red Deer, Fallow Deer)

- Damage: trampling or consuming plants, rubbing antlers on young trees in shelterbelts or perennial plantations.

4. European Hare (Lepus europaeus)

- Damage: gnaws on early-stage crops, especially wheat, barley, rapeseed, carrots, sugar beet, and alfalfa.
- Critical periods: winter (due to food scarcity) and spring.

5. Rodents (Field Mice, Ground Squirrels, Hamsters)

- Damage: consume seeds, stems, and roots, reducing plant density.
- Control: traps, chemical treatments, and encouraging natural predators (e.g., owls, hawks).

6. Wild Birds (Crows, Starlings, Pigeons)
- Damage: consume sown seeds; attack fruits and grains (maize, sunflower).
- Measures: scarecrows, gas cannons, protective netting.

Traditional and Complementary Wildlife Control Measures for Agricultural Protection

While drone technology is increasingly used to detect and deter wild animals from agricultural fields, traditional and complementary control methods remain essential components of integrated wildlife management strategies. These measures, often passive or preventive in nature, play a vital role in minimizing damage caused by species such as wild boars, deer, hares, rodents, and birds. Below are some of the most commonly applied non-technological interventions, along with their benefits and limitations:

A. Electric or Simple Fencing

Description: Fencing is one of the most widespread and effective methods for physically preventing wildlife from entering agricultural land. In areas with high wild boar density, electric fencing is often used due to the species' strength and persistence.

Advantages:
- Provides a continuous physical barrier.
- Highly effective for medium-to-large mammals (e.g., wild boars, deer).
- Electric fences offer psychological deterrence through mild shocks.

Limitations:
- High initial installation and maintenance costs.
- Wild boars may sometimes break through poorly maintained fences.
- Ineffective for smaller animals (e.g., rodents, birds).

B. Shelterbelts (Windbreaks)

Description: Shelterbelts are rows of trees or shrubs planted around fields to reduce wind erosion and serve as ecological barriers.

Advantages:
- Can obstruct the movement of large animals into fields.
- Provides ecological benefits such as soil stabilization, microclimate regulation, and increased biodiversity.
- Long-term and sustainable measure when properly maintained.

Limitations:
- Requires time to grow and establish.
- May also offer cover to certain pests or predators if not managed properly.

C. Acoustic and Visual Deterrents

Description: These devices are designed to frighten or disorient animals through sounds, lights, or visual stimuli. Examples include gas cannons, ultrasonic devices, reflective tapes, scarecrows, and predator decoys.

Advantages:
- Immediate deterrent effect.
- Cost-effective for short-term use.
- Particularly useful against birds and small mammals.

Limitations:
- Animals often habituate to repeated or predictable stimuli, reducing long-term effectiveness.
- Requires frequent repositioning and variation to maintain efficiency.
- May disturb non-target species or nearby human populations.

D. Chemical and Biological Repellents

Description: These are substances applied directly to crops or field borders that produce unpleasant odors or tastes, deterring animals from feeding.

Advantages:

- Easy to apply and integrate with crop treatment routines.
- Can be species-specific depending on the formulation.
- Some are biodegradable and safe for the environment.

Limitations:

- Effectiveness is often temporary and weather-dependent.
- May require repeated application during the growing season.
- Limited availability for certain target species.

E. Habitat Management

Description: Modifying the surrounding landscape to make agricultural areas less attractive or accessible to wildlife.

Examples include:

- Removing nearby hedgerows or brush piles used as shelter.
- Managing water sources and food availability near fields.
- Planting buffer crops to divert animal activity.

Advantages:

- Prevents long-term wildlife habituation to crop areas.
- Can be tailored to local ecological and agricultural contexts.
- Supports coexistence between wildlife and agriculture.

Limitations:

- Requires coordination at the landscape or community level.
- May involve trade-offs with biodiversity conservation goals.

These traditional and complementary wildlife control measures serve as the foundation for protecting crops from animal damage. When integrated with modern technologies such as drones, camera traps, and automated deterrent systems, they form a holistic approach to wildlife management in agriculture. Combining multiple strategies—tailored to specific species, seasons, and field conditions—offers the best chance of long-term success and ecological sustainability.

2. Materials and methods

Drone Technology for the Detection and Deterrence of Wildlife in Agricultural Fields

The use of drones to combat wildlife that damages agricultural crops represents a modern and rapidly evolving approach that offers significant advantages over traditional methods. Unmanned Aerial Vehicles (UAVs) provide enhanced surveillance capabilities, non-lethal deterrence mechanisms, and timely interventions that can mitigate crop losses and reduce reliance on labor-intensive or invasive solutions.

A. Early Detection and Real-Time Monitoring

Drones equipped with thermal or infrared cameras can detect the presence of wild animals—including wild boars, roe deer, hares, and large rodents—even at night or in dense vegetation. This enables precise identification of wildlife entry points and movement patterns across agricultural plots.

Key benefits include:

- Automated patrols during critical hours (dusk, night, and early morning);
- Real-time detection with immediate alerts sent to farmers or relevant authorities;
- Improved planning and rapid response to prevent crop damage.

B. Non-Lethal Wildlife Deterrence

Modern UAVs can also be fitted with sound and light-based systems designed to repel animals without causing harm. This includes:

- Predator-like sounds (e.g., wolf howls or sharp whistles);
- Strobing lights or high-intensity LED flashes, particularly effective at night;
- Hawk-shaped drones simulating the silhouette of a bird of prey.

These deterrents can be integrated into fully automated systems, triggered by motion sensors or operating on pre-programmed patrol routes.

C. Support for Targeted Human Intervention

By streaming live footage and transmitting GPS coordinates, drones allow security teams or wildlife managers to locate and address threats with high precision. In some cases, drones can be used to guide animals away from cultivated areas and redirect them toward safe zones, such as nearby forests or designated wildlife corridors.

D. Damage Mapping and Post-Incident Analysis

In the aftermath of a wildlife incursion, drones are valuable tools for:

- Mapping the exact area affected by the intrusion;
- Estimating the total surface area and value of damaged crops;
- Producing high-resolution photo and video documentation for insurance claims or governmental compensation programs.

Challenges and Limitations

Despite their benefits, several limitations must be considered:

- Wildlife may become habituated to drone presence, reducing effectiveness over time;
- Extended battery life and wind resistance are critical for night-time or long-range missions;
- Initial costs for equipment and trained personnel can be significant;
- Legal restrictions may limit drone operations near protected areas or during certain seasons.

Common Equipment Configurations

Equipment	Application
DJI Matrice drone + FLIR thermal sensor	Nocturnal detection and perimeter patrols
Drones with speakers + LED light modules	Active deterrence through sound and light
AI-enabled drones with real-time object detection	Automated recognition and response

Implementation Recommendations

- Develop a daily flight plan with patrols scheduled at dawn and dusk;
- Integrate drones with fixed sensors and motion detection systems for increased accuracy;
- Coordinate with local wildlife authorities or farm security services;
- Adapt deterrent strategies based on wildlife species, crop type, and seasonal behavior.

In conclusion, integrating drone-based systems into wildlife management strategies offers a proactive and sustainable solution for reducing crop losses. When combined with traditional measures such as fencing, habitat control, and community-based surveillance, drones can significantly enhance agricultural resilience and biodiversity coexistence.

3. Results

The increasing frequency and severity of wildlife-related damage to field crops has necessitated the adoption of smarter, more efficient, and ecologically sustainable protection methods. In response to this challenge, the development of an integrated drone-based system presents a scalable and adaptable solution that combines early detection, non-lethal deterrence, and real-time decision-making.

System Objectives

The primary objectives of the system are:

- To detect the presence of wild animals (e.g., wild boars, roe deer, hares) before significant crop damage occurs;
- To deter animals using non-invasive methods;
- To support rapid intervention and post-event analysis;
- To operate autonomously or semi-autonomously with minimal human input;
- To contribute to sustainable agriculture with reduced ecological impact.

System Architecture
The proposed system includes the following components:
a. Drone Platform
b. Ground Station & Control Software
- A central unit for mission planning, data processing, and system control.
- Features include:
    - Flight path programming based on GPS and geofencing;
    - Real-time video streaming;
    - Alert system (SMS/email) to notify farmers or wildlife authorities.

c. Sensor Network (Optional)
- Ground-based motion detectors or thermal sensors to trigger drone launches in critical zones.
- Weather sensors to optimize flight schedules and battery performance.

d. AI-Based Detection and Recognition
- Implementation of object detection algorithms (e.g., YOLOv5, TensorFlow models) to automatically identify animal species from aerial footage.
- Onboard edge computing using NVIDIA Jetson or equivalent processing units for real-time decision-making.

Operational Workflow
1. **Pre-Detection Phase**: Daily or event-triggered drone patrols scan the field perimeter and hotspots using thermal and visual sensors.
2. **Detection Phase**: Wildlife is identified via thermal signature and AI-based classification; GPS coordinates are logged.
3. **Deterrence Phase**: The drone activates acoustic and/or visual deterrents if the animal remains within the danger zone.
4. **Intervention Support**: If deterrents fail, the system transmits coordinates and a live feed to human responders for intervention.
5. **Post-Event Analysis**: Affected areas are mapped for damage assessment, insurance claims, or compensation purposes.

Sustainability and Advantages
- **Reduced chemical usage**: Eliminates the need for harmful repellents or poisons.
- **Minimal environmental impact**: Non-lethal methods preserve local biodiversity.
- **Cost-efficiency**: Long-term reduction in crop loss and manpower costs.
- **Scalability**: The system can be adapted for different farm sizes, crop types, and regional wildlife profiles.

Implementation Considerations
- **Legal compliance**: Ensure adherence to national regulations on drone flights and wildlife protection.
- **Training**: Operators require basic UAV piloting skills and familiarity with monitoring software.
- **Maintenance**: Regular drone and sensor calibration for optimal performance.

- **Integration**: Can be combined with traditional methods (fencing, shelterbelts) for a hybrid protection strategy.

Conclusion

The development of an integrated drone-based system for combating wildlife damage in agriculture represents a significant advancement in the adoption of precision technologies for sustainable farming. By combining real-time monitoring, intelligent deterrence, and data-driven management, such systems can protect yields, reduce operational costs, and contribute to harmonious coexistence between agriculture and wildlife.

System Architecture

The proposed system includes the following components:

- Type: Multirotor UAVs with vertical take-off and landing (VTOL) capability for flexibility and precision.
- Sensors: Thermal infrared camera for night detection optional LiDAR for terrain mapping.
- Payload: Acoustic emitters (predator sounds, ultrasonic deterrents), LED flashlights or strobes, AI module for real-time detection.

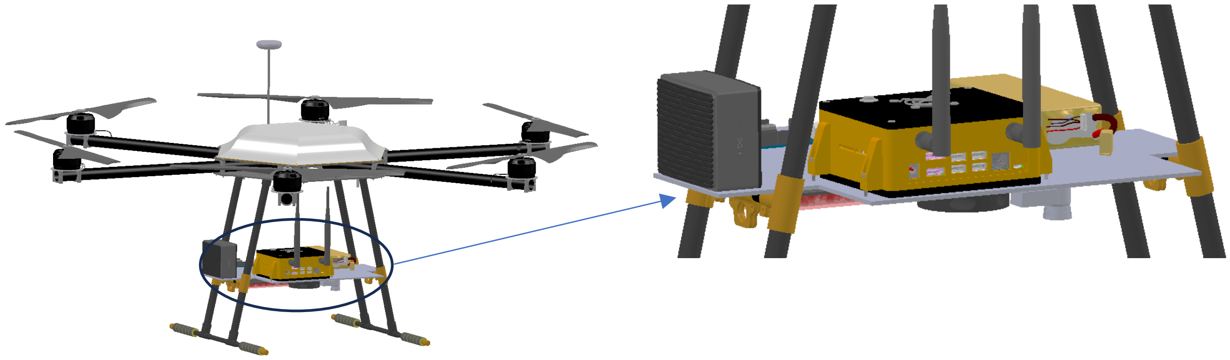
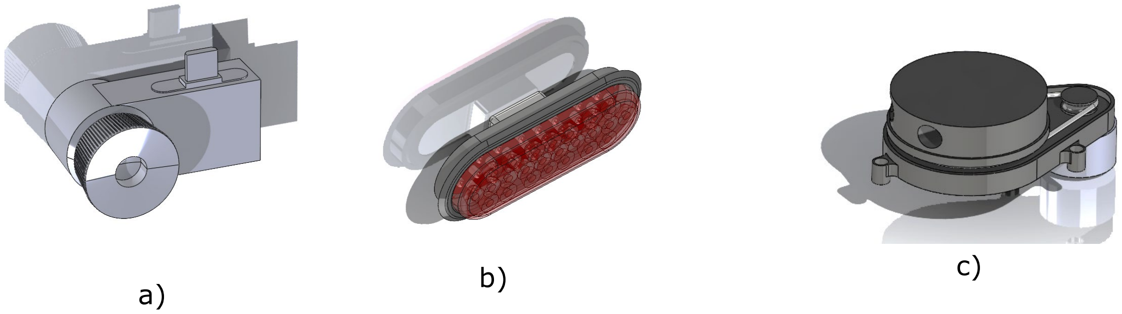


Fig.1. 3d Model of drone with system for combating wildlife to field crops

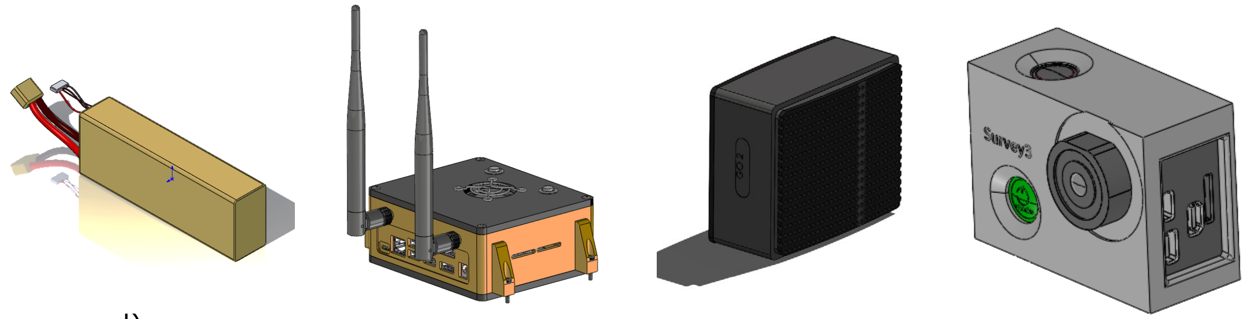
The presented 3D model illustrates a multirotor drone (hexacopter) designed for monitoring and deterring wild animals that cause damage to field crops. The platform is equipped with multiple intelligent components, enabling autonomous operation and effective real-time intervention.

Key components mounted on the drone:

a. Thermal camera mounted on the lower side, vertically oriented for aerial scanning; utilizes infrared imaging to detect animals under low-light conditions.



a) b) c)



d) e) f) g)

Fig.2. a) Seek Thermal CompactXR; b) Stroboscop lights; c) Seek Thermal CompactXR; d) Seek Thermal CompactXR; e) Unitate de procesare – NVIDIA Jetson; f) Difuzor acustic; g) Survey3 RGB Camera

The **Seek Thermal CompactXR** (fig.2.a) is a compact, affordable infrared (IR) thermal imaging camera designed for mobile devices and compatible with Android and iOS systems. Its small form factor, extended range optics, and plug-and-play functionality make it suitable for integration into low-cost UAV systems for wildlife detection, surveillance, and agricultural applications.

b. High-intensity LED lighting system – A strobe-type LED light (Fig. 2.b) used for the visual deterrence of animals; mounted on the underside of the support plate, below the camera, for precise ground illumination.

c. Acoustic speaker (Fig. 2.f) – Capable of emitting loud or predator-specific sounds (e.g., wolf howls) to scare animals; controlled by the AI processing system.

d. Processing unit – NVIDIA Jetson (Fig. 2.e) – Runs artificial intelligence-based recognition algorithms (e.g., YOLOv5, TensorFlow); receives video feed from the cameras and responds in real time.

e. Auxiliary control board (e.g., Arduino) – Mounted on the support plate; controls the signal output to the lights and speaker; receives instructions from the Jetson via GPIO or UART.

f. Dedicated battery for auxiliary systems (Fig. 2.d) – Powers the sensors and electronic boards independently from the propulsion system.

g. LiDAR (Fig. 2.c) – Used for terrain mapping and generating elevation profiles.

h. Survey3 RGB Camera – Used for a can definitely be used for mapping affected areas in the context of **damage assessment, insurance claims and compensation purposes**

All modules are mounted on a **rigid base plate**, likely made of composite or aluminum. Signal and power cables are organized to minimize electromagnetic interference. The platform includes multiple connectivity ports (USB, HDMI, UART), visible in Image 3, allowing external configuration and data transfer.

Operational Workflow: The thermal camera detects a heat signature, which is analyzed by the Jetson module to classify the animal (e.g., wild boar); if the animal is within a danger zone, Jetson commands the flight controller to hold position and simultaneously sends a signal to the Arduino to activate the LED light and sound deterrent, while also transmitting the GPS location to the farmer via a cloud platform or mobile application; if the animal persists, a live location feed is sent to the intervention team for immediate response.

4. Conclusions

The integration of drone-based systems into agricultural wildlife management offers a significant step forward in precision farming and sustainable environmental practices. By combining advanced sensors, artificial intelligence, and autonomous flight capabilities, these systems address critical challenges in preventing and mitigating wildlife-induced crop damage.

The developed platform enables early detection of animal intrusions through thermal and RGB imaging, allowing for real-time identification and classification of species such as wild boars, deer, and hares. Equipped with non-lethal deterrents—including acoustic signals and strobe lighting—the drone can effectively repel animals without causing ecological harm. The addition of an AI processing unit (e.g., NVIDIA Jetson) ensures on-board analysis and immediate response, minimizing delay and human intervention.

Furthermore, the system supports targeted human intervention and post-incident analysis, providing accurate mapping of affected areas using RGB and LiDAR sensors. This not only facilitates insurance claims and compensation processes but also contributes to long-term monitoring and strategic planning.

Although challenges such as battery autonomy, equipment cost, and legal restrictions remain, the benefits in terms of crop protection, environmental impact reduction, and operational efficiency are substantial. When integrated with traditional measures like fencing and habitat management, this drone-based approach forms a comprehensive and adaptive strategy for wildlife control in agriculture.

Ultimately, the use of intelligent UAV systems enhances agricultural resilience, promotes sustainable land use, and fosters a more balanced coexistence between farming activities and natural ecosystems.

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Review

CONTROLLED ENVIRONMENT AGRICULTURE

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Abstract: Controlled Environment Agriculture (CEA) is a technology-based approach to food production. The goal of CEA is to provide protection and maintain optimal growing conditions throughout the crop's development. Production takes place in an enclosed growing structure, such as a greenhouse or building. Plants are often grown using hydroponic methods to deliver the right amounts of water and nutrients to the root zone. CEA optimizes the use of resources such as water, energy, space, capital, and labor. CEA technologies include hydroponics, aeroponics, aquaculture, aquaponics, etc. There are various techniques available for growing food in CEA. The more viable option is vertical farming. Vertical farming has the ability to produce crops year-round in a controlled environment, with the possibility of increasing yields by adjusting the amount of carbon and nutrients received by the plants. In terms of urban farming, CEA can exist inside existing buildings, such as abandoned buildings.

1. Introduction

Throughout human history, agriculture has been the foundation of civilization. The first forms of agriculture, which emerged more than 10,000 years ago, allowed people to move from a nomadic to a sedentary lifestyle, thus creating the premises for social, cultural and economic development. Agriculture has evolved continuously – from the rudimentary cultivation of cereals in the Euphrates Valley, to the introduction of the plow in Antiquity, then to mechanization in the 19th century and to the Green Revolution in the 20th century. However, despite these advances, the global agricultural system today faces a series of unprecedented challenges, which threaten the very food security of humanity. Against the backdrop of the exponential growth of the world population, estimated to exceed 9.7 billion people by 2050, the demand for food will increase by approximately 60% compared to the current level. This pressure comes in a context marked by severe climate change, biodiversity loss, soil degradation, lack of freshwater resources and accelerated urbanization. Traditional agriculture, dependent on natural cycles and climatic conditions, is becoming increasingly vulnerable to these destabilizing factors, [1,2]. Consequently, a profound transformation of the way we produce food is required – a transition from extensive agriculture, with significant ecological impact, to efficient, sustainable and resilient production systems. In this equation of food sustainability, Controlled Environment Agriculture (CEA) is emerging as a viable and innovative alternative. It proposes an integrated approach, in which technology, engineering and plant science converge to allow the cultivation of food in environments completely or partially isolated from external conditions, optimized for maximum efficiency and minimal environmental impact, [2].

Controlled environment agriculture is an agricultural system that uses closed or semi-closed spaces, such as greenhouses, climate-controlled containers, culture chambers or vertical farms, in which all the environmental factors necessary for plant growth – light, temperature, humidity, carbon dioxide, air circulation, nutrients – are strictly monitored and regulated with the help of technology. This method allows for constant, uniform and predictable agricultural production, regardless of season, geographical location or external climatic conditions. Unlike conventional agriculture, where yields are often influenced by weather variability, crop diseases and soil quality, CEA creates a controlled artificial ecosystem, in which plants benefit from the best possible conditions at each stage of development. The result is a much higher productivity per unit area, reduced water and fertilizer consumption, as well as an almost total elimination of pesticides, thanks to the sterile environment, [3]. CEA can take several technological forms, depending on the nature of the system: hydroponics (cultivation of plants in nutrient solution without soil), aeroponics (nutrients in the form of aerosols), aquaponics (integration of plant culture with fish farming), or cultivation in totally isolated environments with artificial lighting. All these methods are based on advanced infrastructure: humidity and pH sensors, automatic irrigation and fertilization systems, monitoring software and artificial intelligence algorithms, [1, 3].

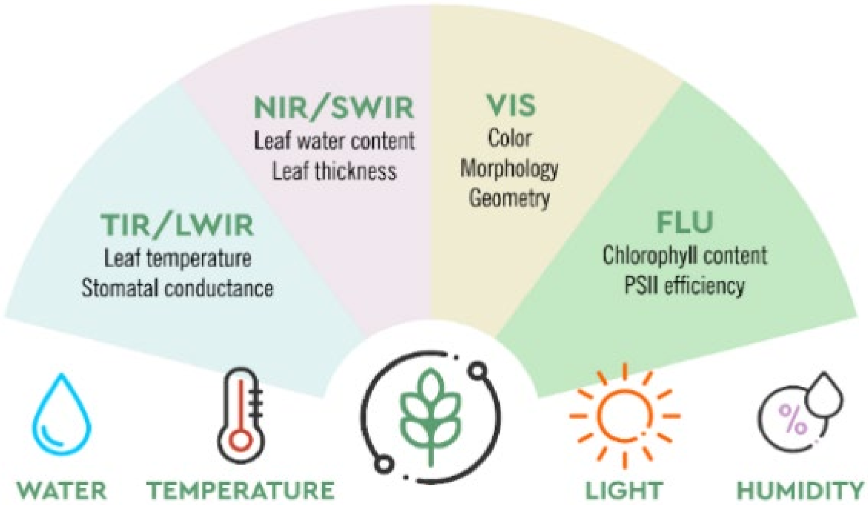

Figure 1. Controllable variables in CEA,[6]

The motivation for the development of CEA in the current global context. The global climate is undergoing rapid transformation. Extreme phenomena – droughts, floods, storms, heat waves – are already affecting farmers' ability to obtain stable harvests. In many regions of the world, the growing season is shortening or becoming unpredictable, which drastically reduces food security. Traditionally fertile agricultural areas, such as the Nile Delta or the agricultural regions of California, are facing decreasing access to water and soil salinization. In this context, CEA provides a predictable and stable agricultural environment, where production is not threatened by the vagaries of nature. Farmers can cultivate continuously, all year round, reducing the economic risks associated with crop loss,[3,4]. Thus, CEA not only complements, but in many cases can replace conventional agriculture in areas affected by climate change.

Urbanization and the decline of agricultural land. Over 56% of the world's population lives in urban areas today, a percentage that will reach over 70% by 2050. With the expansion of cities, agricultural areas around them are increasingly transformed into residential, industrial or commercial areas. At the same time, the distance between producers and consumers increases, which implies long supply chains, transport, storage and food waste. CEA allows the integration of agricultural production directly into the urban environment, through vertical farms located in buildings, on rooftops or even underground. This proximity to the consumer significantly reduces the carbon footprint associated with transport and contributes to the development of local circular economies,[5,6].

Natural resource crisis. The essential resources for agriculture – water, fertile soil, fuels – are increasingly limited. Approximately 70% of global water consumption is for agriculture, and over 30% of agricultural land is already degraded or subject to erosion. In this context, the CEA offers a model for efficient and responsible use of resources:

- water consumption reduced by up to 90% compared to traditional irrigation;
- water reuse through recirculation systems;
- avoiding overfertilization and groundwater pollution;
- eliminating the need for plowing or intensive land use.

The global crisis caused by the COVID-19 pandemic has exposed the vulnerability of global food supply chains. Transport disruptions, border closures and dependence on imports have reduced the availability of certain products, increased prices and exacerbated inequalities in access to food. In this context, CEA has demonstrated its ability to operate autonomously, providing a local and stable source of food. Indoor production, carried out in closed spaces, does not depend on external factors and can ensure food continuity even in conditions of social isolation or trade blockades, [6].

Depending on the country or region or type of grower, different words are used to describe the same thing. Here is a brief description of the different growing environments for AMC: Indoor Growing / Indoor Farming Indoor growing and indoor farming refer to the production of crops that use supplemental lighting, such as LED lights instead of sunlight, and provide the ability to control the environment. This type of controlled environment farming can include rooms, warehouses, containers, factories, and other converted indoor spaces that are not typically designed for growing crops, [6,7].

Figure 2. Indoor Farming Indoor, [6,7]

Vertical Farming is the production of crops using vertical space. Plants can be stacked horizontally or in tall towers. This style of farming is great for small spaces, such as shipping containers or other high-density spaces, because it requires less land for cultivation, [3,14].

Figure 3. Vertical Farming, [3]

A greenhouse is a glass or polycarbonate structure that uses sunlight to grow crops. Variables such as temperature, humidity, and sunlight must be carefully considered when growing produce in greenhouses, especially during the summer months.

Figure 4. Greenhouse,[9]

Protected cultivation. Protected cultivation refers to crops that are grown outdoors with some protection from the elements, e.g. in sunrooms, greenhouse tunnels or canopy. Pest control is more difficult to manage because the crops are exposed to the elements, however protection can provide value when it comes to rain, hail and frost, [8,9].

2. Materials and methods

In a crop production environment, plants can be grown using a variety of methods. By far the most popular method is hydroponics. Here are some types of growing methods you can use in controlled environment farming.

Hydroponics is the growing of plants without soil as a medium while providing water, nutrients, and oxygen. Plants can be grown in a variety of media such as sand, gravel, rockwool, coconut fiber, and sponge cubes. It is a sustainable way to grow with water - expect potential savings of between 70% and 90%, depending on the type of crop and your setup. There are different types of hydroponic systems, including: - N.F.T. (Nutrient Film Technique) - Drip System - Ebb and Flow (also known as Flood and Drain) - Wick - Water Culture (also known as Deep Water Culture) Crops grown using this method include microgreens, greens, tomatoes, peppers, strawberries, herbs and medicinal cannabis, [5,6].

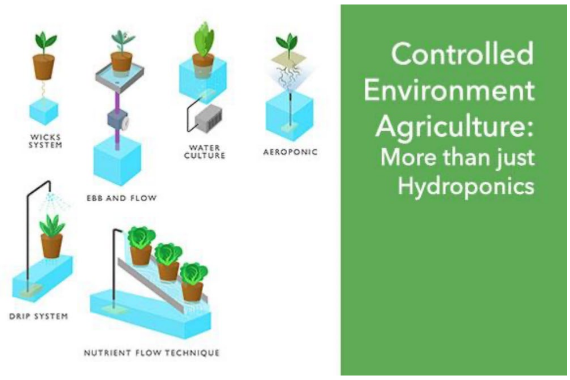

Figure 5. Hydroponics, [5,6]

Aeroponics is the growing of plants without soil and using little water. The plant's roots are suspended in the air and sprayed with a solution of nutrients and water. The roots are generally in a closed environment to ensure that the nutrient mist is captured by the root structures, [11]. Aeroponics is typically used in greenhouses, using sunlight as the primary light source, with supplemental lighting if necessary. Aeroponics has been noted as the most sustainable type of water growing, using 90% less water than some hydroponic systems, which are already considered sustainable themselves, [6]

Figure 6. Aeroponics, [6,11]

Aquaponics is a controlled environment farming method that uses a combination of aquaculture (fish farming) and hydroponics. In a thriving ecosystem, waste from the fish (ammonium and urea) and bacteria in the system provide the plants with all the nutrients they need. Aquaponics relies on fast-growing fish (tilapia, perch, catfish, trout, etc.) to meet the plants' needs and can be set up indoors because it doesn't require soil, [12,15]. The water can then be recycled back to the fish. Each species feeds the other without the need for chemical fertilizers.

Figure 7. Aquaponics, [12]

Fogponics (also known as mistponics) Fogponics has been described as the next phase of aeroponics technology. Using the same basic premise of suspending the root system in the air in a closed environment and delivering water and nutrients to the plant, fogponics uses droplets that are essentially vapor. The nutrient-rich mist is delivered to the stems, leaves, and roots for faster and better absorption**,** [4,5,6]

Figure 8. Fogponics, [4]

Controllable Variables:

- Temperature (air, nutrient solution, root zone, leaf)

- Humidity (% RH)
- Carbon Dioxide (CO_2)
- Light (intensity, spectrum, duration and intervals)
- Nutrient concentration (PPM, EC)
- Nutritional pH (acidity)
- Pests

AMC facilities can range from 100% environmentally controlled closed loop systems, to fully automated greenhouses with computerized controls for watering, lighting and ventilation, to low-tech solutions such as cloches or plastic sheeting over field-grown crops and plastic-lined tunnels. AMC methods can be used to grow literally any crop, although the reality is that a crop must be economically viable and this will vary considerably due to local market prices and resource costs.

3. Results

One of the most obvious achievements of controlled environment agriculture (CEA) is the spectacular increase in yields. In a confined space, with total control of environmental factors, plants grow faster, more evenly and healthier than in the open field. Various studies and pilot projects have demonstrated the following advantages, [11,13]:

- Lettuce grown hydroponically in a vertical farm can achieve 10–12 production cycles per year, compared to 2–3 outdoors.
- Tomatoes grown in climate-controlled greenhouses can produce 3–5 times more per square meter than those grown in soil.
- Microgreens can be harvested in 7–14 days, providing a fast and continuous source of nutritious food. This efficiency is due to the precise control of light, nutrients, temperature and humidity, which virtually eliminates losses caused by weather phenomena, disease or water stress.

Reduced resource consumption. CEA offers outstanding performance in terms of resource efficiency: Water. In a closed hydroponic system, water consumption can be reduced by up to 90–95% compared to conventional agriculture. Recirculation and the lack of direct evaporation make CEA a viable solution for arid regions. Soil and farmland CEA allows soilless cultivation, reducing the pressure on fertile land, which is becoming increasingly scarce. Vertical farms can also be located in cities, close to consumers, contributing to urban agriculture and reducing dependence on rural farmland, [12].

Pesticides By eliminating soil pathogen contamination and isolating it from the outside environment, CEA dramatically reduces or completely eliminates the use of pesticides, resulting in cleaner and safer food for consumers.

Energy CEA requires high energy consumption, especially for artificial lighting and air conditioning. However, modern farms implement [3, 14,16]:

- photovoltaic panels for green energy;
- heat recovery;
- energy-efficient LED lighting systems.

In some cases, farms can become energy neutral, especially when integrated into green buildings or smart grid systems.

Economic and social advantages CEA brings not only ecological, but also economic benefits: Reduction of post-harvest losses. Through localized production, close to consumer markets, CEA reduces food losses that occur in the logistics chain. Fruit and vegetables no longer have to be transported thousands of kilometers, preserving their freshness and nutritional value. Creation of new specialized jobs. Controlled farms require qualified personnel: horticultural engineers, plant nutrition specialists, IT operators and technicians. This opens up prospects for young people and graduates in the fields of agriculture, biotechnology and computer science. Constant production, all year round, [15]. CEA does not depend on seasons or weather conditions. Thus, continuous agricultural production is possible, with constant weekly deliveries, which stabilizes the market and provides economic predictability.

Current limitations and challenges. Although promising, controlled environment agriculture also faces difficulties:

- High investment costs: setting up a complete CEA system (including lighting, automation, sensors) is 5–10 times more expensive than conventional agriculture.
- Energy consumption: without the integration of renewable energy, operational costs can become prohibitive.
- Limitation to certain crops: large plants (wheat, corn, sunflower) are not profitable in CEA, which is currently only viable for small to medium-sized horticultural crops.
- Limited know-how: CEA involves a complex combination of agronomy, electronics, IT and biochemistry. Without adequate preparation, many projects can fail.

4. Conclusions

CEA brings to the forefront a systemic and technologically advanced approach, in which food production is transformed from a process exposed to hazard into a predictable, efficient and sustainable one. By fully controlling environmental factors – light, temperature, humidity, CO_2, nutrients – agriculture becomes independent of climate, seasons or geographical location, and can be practiced anywhere and anytime. Multiple benefits of agriculture in a controlled environment are highlighted, the most important of which are:

- *Increased productivity*: Crops with yields much higher than those obtained in the open field, due to the elimination of losses caused by uncontrollable factors (drought, pests, frost).
- *Reduced resource consumption*: Savings of up to 90% of water used, reduction to zero of pesticides, elimination of the need for fertile agricultural soil.
- *Ecological sustainability*: CEA promotes an agricultural model that does not deplete the *soil, does not pollute the waters and does not depend on deforestation or land expansion.*
- *Food Safety*: Fresh, locally grown, pesticide-free, fully traceable produce, consistently available, regardless of season or region.
- *Technological Innovation*: Integrating artificial intelligence, automation, sensors and data systems into agriculture, transforming the agri-food sector into a cutting-edge field.

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Article

DENITRIFACTION AND WATER QUALITY MANAGEMENT IN AQUAPONICS SYSTEMS

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Keywords: denitrifaction, water quality, aquaponics systems, human nutrition**.**

Abstract: Aquaponic systems integrate aquaculture and hydroponics in a closed-loop environment, requiring effective water quality management to maintain optimal conditions for both fish and plants. One of the key processes in water treatment is denitrification, which plays a crucial role in removing excess nitrogen compounds, particularly nitrate, from the system. The accumulation of nitrogenous waste, originating from fish metabolism and uneaten feed, can lead to toxic conditions if not properly managed. Biological filtration, including nitrification and denitrification, helps convert ammonia into nitrate and subsequently into nitrogen gas, which is released into the atmosphere. Effective management strategies, such as optimizing biofilter performance, controlling dissolved oxygen levels, and maintaining a balanced microbial community, are essential to ensure water quality remains within safe parameters. By implementing proper denitrification techniques and monitoring key water parameters, aquaponic systems can achieve sustainable production while minimizing environmental impact.

1. Introduction

Fish are fed with feed that has a high protein content. Most of the food introduced into the system is consumed by the fish, while the uneaten food decomposes within the system. The metabolic products of the fish (metabolites) include carbon dioxide, ammoniacal nitrogen, and fecal solids. The dissolved nitrogen from the fish is excreted mainly in the form of urea and ammonia. If uneaten food and the mentioned metabolites remain in the system, the concentrations of carbon dioxide and ammoniacal nitrogen in the culture water may reach high levels[1,2], meaning they will no longer fall within the optimal range from a technological standpoint.

In fish tanks, ammonia exists in two forms, which together are referred to as total ammoniacal nitrogen or TAN ($NH4+ \leftrightarrow NH3 + H+$). NH4+ is the ammonium ion that forms when an ammonia molecule (NH3), in which the nitrogen (N) has a lone pair of non-bonding electrons, comes into contact with a hydrogen ion (hydron) H+ derived from an acid or water. The nitrogen acts as the donor, while the hydrogen ion is the acceptor. Due to the positive charge of the hydrogen ion, the entire ammonium ion becomes positively charged, [3,4].

NH3 – Ammonia is a chemical compound composed of one nitrogen atom and three hydrogen atoms. It exists in a gaseous state, has the chemical properties of a base, is toxic, has a pungent odor, and is lighter than air.

NO2- – Nitrite is an inorganic anion and the conjugate base of nitrous acid. It consists of one nitrogen atom and two oxygen atoms bonded identically, forming a 120° angle.

NO3- – Nitrate is a polyatomic ion and the conjugate base of nitric acid. It consists of a central nitrogen atom surrounded by three identical oxygen atoms in a trigonal planar arrangement. The nitrate ion has a formal negative charge, with each oxygen carrying a separate charge of -2/3 and the nitrogen atom having a charge of +1. Almost all inorganic nitrates are soluble in water under standard temperature and pressure conditions.

Nitrification. The nitrification process is a two-step biological oxidation of ammonia to nitrate. This process is carried out by autotrophic bacteria that use ammonia and nitrites as growth substrates to generate energy for cellular activity and reproduction, [5]. The two steps of the nitrification process and the overall reaction are presented below:

$$2NH_4^+ + 3O_2 \xrightarrow{bacteria} 2NO_2^- + 2H_2O + 4H^+ + energy$$

$$2NO_2^- + O_2 \xrightarrow{bacteria} NO_3^- + energy$$

$$NH_4^+ 2O_2 \rightarrow NO_3^- + H_2O + 2H^+ + energy$$

The effectiveness of the nitrification process depends on oxygen concentration, temperature, biomass retention time, alkalinity, and pH. Nitrifying bacteria are strictly aerobic and can only nitrify in the presence of dissolved oxygen (DO).

Denitrification. The biological denitrification process involves the conversion of nitrates into gaseous nitrogen in the absence of oxygen. This process is carried out by certain heterotrophic bacteria, known as heterotrophic denitrifying bacteria, which have the ability to use nitrates and nitrites as electron acceptors in the oxidation of organic matter. The efficiency of the denitrification process is influenced by the absence of dissolved oxygen, the presence of an adequate and active population of denitrifying bacteria, pH, temperature, nutrients, and redox potential, [6].

Regarding the recirculating aquaculture subsystem (RAS), the main technological objective is to ensure environmental conditions that closely match the eco-physiological requirements of the cultured aquatic species (usually fish). Water quality in a recirculating aquaculture system (RAS) is critically determined by its concentration of dissolved oxygen, un-ionized ammoniacal nitrogen, nitrites, and carbon dioxide. Additionally, nitrate concentration, pH levels, and alkalinity are important parameters for assessing water quality. In recirculating aquaculture systems, water parameters must be monitored and maintained within optimal limits for the cultured species, including temperature, dissolved oxygen, ammonia, nitrites, carbon dioxide, pH, suspended solids, chlorides, and nitrates,[7].

Achieving maximum profitability in aquaculture requires a high growth rate of biomass and the shortest possible time to reach a marketable size. Traditionally, excess nitrate in aquaculture has been reduced through water exchange or biological denitrification filters, [7]. To maintain these concentrations within the optimal range, recirculating aquaculture systems consist of an integrated set of processing units that treat water for reuse in culture tanks. All recirculating systems require basic processing units to remove solid waste and biological filters designed to oxidize ammoniacal nitrogen—highly toxic—into nitrites, and then into nitrates, which are relatively non-toxic.

2. Materials and methods

Determining the best water management in an aquaponic system can be challenging due to the fact that the three main organisms involved in the system—fish, plants, and bacteria—perform optimally at different temperatures and pH levels (see Table 1). This often leads to the need for a compromise, depending on the types of plants and fish chosen for production. A good starting point for warm-season vegetables, fish, and nitrifying bacteria would be to maintain the water pH between 6.5 and 7.5. The absorption of certain nutrients by plants is more efficient at a pH of 6.5.

Table 1. Optimal Temperature and pH for Growth and Yield of Selected Organisms in Aquaponic Culture, [5]

Organism	Optimal Temperature (°C)	Optimal Temperature (°F)	Optimal pH
Tomatoes, peppers, and cucumbers	27–29 (day) 17–22 (night)	80–85 (day) 62–72 (night)	5.5–6.5
Lettuce	18–24	65–75	5.5–6.5
Tilapia	28–32	82–90	6.0–8.5
Catfish	28–30	82–86	6.5–9.0
Common carp	25–30	77–86	7.0–9.0
Nitrifying bacteria	25–30	77–86	7.0–8.0

The nitrification rate increases with the reaction rate at a pH of 7.5, which transforms toxic ammonia (NH3) into nitrate nitrogen (NO3-), the preferred nitrogen source for plants. At pH 7.5, there may be a micronutrient deficiency in plants (mainly iron and manganese), but this can be overcome with foliar sprays containing the deficient nutrients. Many factors can influence the pH of water in the system, including: Nitrification produces hydrogen ions and consumes carbonate ions, thus lowering the pH of the water. The assimilation of nitrate ions by plant roots results in the secretion of hydroxide ions, thereby increasing the pH. The natural pH of the replacement water source can increase or decrease the pH of the aquaponic system. To raise the pH to the recommended level, calcium hydroxide or potassium hydroxide is added. To lower the pH to the recommended level, sulfuric, phosphoric, nitric, or hydrochloric acid is used. These operations must be carried out with caution: Any chemical substance, such as pH regulators, which can rapidly change the water quality in the tanks, should be added to a smaller reservoir first and then slowly added to the fish tank, so that water quality changes gradually, reducing stress for the fish. The use of calcium carbonate (lime) or magnesium carbonate (dolomite) can provide a slower pH increase and a long-lasting buffer, [8].

The effect of pH on the level of toxic ammonia (NH3) is another important aspect to consider. Water temperature and pH will affect the percentage of each compound in the TAN equilibrium. For example, at 82ºF (28°C), the percentage of NH3 increases by nearly a factor of 10 for each 1.0 increase in pH, with 0.2%, 2%, and 18% of TAN for pH 6.5, 7.5, and 8.5, respectively. The beneficial nitrification rate, which converts toxic ammonia into plant-nutritive nitrate, also increases as the pH rises from 6.5 to 8.5, [9], using NH3 as the starting substrate for the reaction. Therefore, growers should consider the balance between pH and toxic ammonia, taking into account the sustainability factor, in managing the biological nitrogen production of nitrate.

In addition to regular pH and TAN measurements, periodic measurements of oxygen concentration are necessary. The most common causes of fish mortality are high ammonia levels (>2 ppm) and low oxygen levels (<3 ppm) over prolonged periods (ppm = parts per million). These conditions can be exacerbated if high fish densities and feeding levels are maintained in the tanks. A reasonable fish density for small farms is 15–20 kg/m3 of aquaculture tank. For higher densities (up to 60 kg/m3), 24-hour monitoring, backup pumps, and ready-to-start generators in case of power outages are required. In emergency situations with insufficient oxygen, feeding should be stopped, and aeration and water circulation should be increased until oxygen levels return to safe levels (>4 ppm).

System sizing recommendations depend on several variables. RAS recommendations suggest that 5%–10% of the water volume in the fish tanks should be discharged daily and replaced with fresh water to help maintain clean water, [10]. If the designed hydroponic subsystem is large enough and has enough plants to absorb this discharged water through plant absorption and system evaporation (evapotranspiration), the resulting aquaponic system can operate with near-zero water discharge for both production systems. To achieve a sustainable system with minimal water discharge into the environment, the hydroponic subsystem should be much larger in area than the aquaculture subsystem. The aquaponic system for lettuce/tilapia, with floating plant supports, uses a ratio of 7.3/1, plant surface area per fish surface area. For larger plants, such as cucumbers and tomatoes, more water is used than for lettuce, requiring more than 2 liters of water per plant per day. Given that plants are often grown in different stages of development, from seedlings to mature plants, in order to maintain the harvest throughout the year using the aquaponic system's water, an average water use of 1 liter per plant per day can be considered when sizing the system for larger plants, [10].

To help maintain water quality, additional filtration of solids from the water tank is usually necessary, separate from the biofilter with nitrifying bacteria, especially in the case of high fish density. Plants also play a role as a biofilter by removing ammonium (NH_4^+) from the system's water, which reduces the concentration of toxic ammonia (NH_3) in the TAN equilibrium ($NH_4^+ \leftrightarrow NH_3 + H^+$). However, research suggests that nitrification is much more important than plant absorption for biofiltration of toxic ammonia, [11], and only through nitrification can ammonia be converted into nitrates, which are the richest in mineral nutrients required by plants.

The solid wastes that appear in a recirculating aquaculture system are represented by uneaten food, fish feces, algae, and bacterial biomass from the biological filters. The dissolved oxygen in the water is consumed in the process of bacterial decomposition of the solid feces and uneaten food, resulting in ammonia nitrogen formation, [2,4]. Therefore, residual solids must be removed from the fish tanks as quickly as possible. Another source of solid particles in an aquaculture system that causes problems is the microfauna, which consists of the total bacterial populations present in the water mass. The existence of bacterial biomass is determined and favored by the presence of organic matter and nutrients in the system. The bacterial population develops either dispersed in the water mass or as an organic film that forms on the walls of the growth tanks, pipes, and primarily in the biological filter, [7,8].

If sludge deposits accumulate in thick layers, these residues will decompose anaerobically (without oxygen), producing methane and hydrogen sulfide, which are highly toxic to fish. Although the degradation of solid waste consumes oxygen and produces ammonia, it serves as a habitat for nitrifying bacteria. During the growth of fish, the fish biomass increases per unit of the system. It is generally accepted that the rate of sludge production and nutrient assimilation used as food for fish in a recirculating system depends on the life cycle of the fish, so the sludge production rate can vary.

Residual solids can be classified into four categories: sedimentable, suspended, floating, and dissolved. In recirculating aquaculture systems, sedimentable and suspended solids can become a problem if the water exchange rate is low.

3. Results

Sedimentable solids (> 100 µm): These solids are considered sedimentable if they settle at the bottom of the tank in less than one hour under calm water conditions. These solids can be removed as they accumulate using appropriate drainage structures designed for the construction and positioning. In general, they are removed from the recirculating aquaculture system (SAR) through the use of various devices or methods of decantation, such as centrifugal separators, settling chambers, and inclined plate separators, [12].

The removal of sedimentable solids can be enhanced by using components located within the culture tanks, such as modified sumps or separate configurations. Another method for controlling sedimentable solids involves keeping them in suspension through continuous agitation and removing them from the wastewater outside the culture tank. These solids must be removed from the system with minimal turbulence and mechanical agitation, [13].

Suspended solids (<100 µm): The main difference between suspended solids and sedimentable solids is practical in nature. Under the specific conditions of water circulation in culture tanks, suspended solids do not settle at the bottom and cannot be easily removed through sedimentation tanks (settling chambers), [10,11]. These types of solids can be removed using a mechanical filter, such as a granular medium filter (pressure sand filters) or screen filters (e.g., inclined screens, rotating drum filters, conveyor belt filters).

In a recirculating aquaculture system, controlling suspended solids is more difficult. To the extent that suspended solids cannot be entirely removed from the culture tanks, they can significantly limit the carrying capacity of the system [15].

Fine and dissolved solids (<30 µm): In a culture tank, fine solids make up more than 50% of the total content of suspended solids. Fine suspended solids increase the system's oxygen demand, as they are largely composed of proteins and also significantly contribute to increasing the system's oxygen requirements. Dissolved and fine solids cannot be easily removed economically through sedimentation or various filtration technologies. The usual method for removing them from wastewater is separation by foam (flotation). The composition and construction of recirculating aquaculture systems (RAS) must maximize the rate of ammonia nitrogen (TAN) removal to enhance water reuse within the system and minimize its impact on fish produced for commercial purposes. Biological filters with high TAN removal rates are capable of effectively eliminating the impact of ammonia nitrogen in RAS, [15].

Nitrites bind to hemoglobin, resulting in methemoglobin. This form is unable to bind and transport oxygen, which impairs the fish's respiratory process. In this case, fish behave as though they are experiencing oxygen stress (they surface more frequently, reduce feeding drastically, and become lethargic). The concentration of nitrites in culture water should not exceed 10 mg/l for prolonged periods of time, with an optimal concentration during production being below 1 mg/l, [16].

Nitrite concentrations should be monitored daily. The toxicity of nitrites varies by species. Generally, fish species with scales are more tolerant of high nitrite concentrations than species without scales, such as catfish,[4,5,10].

Nitrite toxicity can be reduced or blocked by chloride ions. If nitrite concentrations are toxic, feeding should be reduced, fresh water should be added to the system, or salt (NaCl) can be introduced, [13,14].

Nitrates typically do not present a major issue for water quality management in recirculating systems. Literature suggests that cultured fish species can tolerate very high nitrate levels (≥ 200 mg/l). With proper management, nitrate concentrations in culture water do not reach such high levels in recirculating systems. The nitrate levels that could potentially cause significant problems remain unknown for many aquatic species, as sensitivity to nitrates changes ontogenetically, [17]. The chemical reactions in a nitrification filter, accompanied by the release of energy in the form of heat, occur during the oxidation process by *Nitrosomonas* sp. and *Nitrobacter* sp. bacteria, as follows:

***Nitrosomonas* sp:** $NH_4^+ + 1{,}5O_2 \rightarrow 2H^+ + H_2O + NO_2^-$

***Nitrobacter* sp:** $NO_2^- + 0{,}5O_2 \rightarrow NO_3^-$

The hydrogen ions produced during these reactions lead to a decrease in pH, which causes an increase in the acidity of the water. The nitrification rate can be controlled by nitrite oxidizers. However, this situation typically occurs only under improper technological management or during transient imbalances. Nitrite oxidizers are generally known to have higher oxidation rates than ammonia oxidizers, and thus, low nitrite levels are typical in a balanced filter. However, nitrite oxidizers have a lower reproduction rate than ammonia oxidizers. Since nitrates cannot be further oxidized through nitrification, they will accumulate in the system. Current environmental regulations aim to limit the amount of water that can be consumed or discharged, which restricts the ability to use large amounts of water to eliminate excess nitrate. Denitrification filters can be costly, and as aquaculture activities become more restricted in terms of water consumption, nitrates will become a significant issue.

The composition and construction of recirculating aquaculture systems (RAS) must maximize the removal rate of ammonium nitrogen to enhance water reuse within the system and minimize its impact on the fish grown for production. Biological filters with high TAN (Total Ammonia Nitrogen) removal rates are capable of effectively mitigating the impact of ammonium nitrogen in RAS. Nitrites bind to hemoglobin, resulting in methemoglobin formation. Methemoglobin is unable to bind and transport oxygen, thereby affecting the respiration process of fish. In such cases, fish exhibit signs of oxygen stress (they rise to the surface, drastically reduce feeding, and become lethargic). The nitrite concentration in culture water should not exceed 10 mg/L for extended periods, while the optimal concentration during operation should remain below 1 mg/L, [17,18]

Nitrite concentrations must be monitored daily. The degree of nitrite toxicity varies depending on the species. In general, scaled fish species are more tolerant of high nitrite concentrations than scaleless species, such as catfish, [4,6]. Nitrite toxicity can be reduced or blocked by chloride ions. If nitrite concentrations reach toxic levels, feeding should be reduced, and the system should be supplied with fresh water or salt (NaCl) should be added, [7,18].

Nitrates are not typically a major concern in water quality management within a recirculating system. The specialized literature indicates that cultured fish species can tolerate extremely high nitrate levels (≥ 200 mg/L), [19]. With proper management, nitrate concentrations in culture water do not reach such high levels in recirculating systems. The nitrate levels that could potentially cause significant concerns remain unknown for many aquatic species, as nitrate sensitivity varies ontogenetically.

4. Conclusions

In recirculating aquaculture systems (RAS), to ensure maximum fish growth and optimal bacterial efficiency in the biofilter, water quality must be maintained at the highest level, as nitrogen is an essential nutrient for all living organisms, found in proteins, nucleic acids, nucleotides, and pigments.

Recirculating aquaculture systems (RAS), in which fish tanks are placed on land and the effluent from the fish tanks is biologically treated and then recirculated back into the fish tanks, provide an opportunity for large-scale ecological fish production that aligns with sustainability principles. To take advantage of RAS, water exchange must be kept as low as possible. This requires meeting certain water treatment standards, such as maintaining an efficient nitrification and denitrification system and removing organic waste. Ammonia, a metabolic byproduct, will accumulate and reach toxic levels in the culture water if it is not removed. In closed aquaculture systems, where daily water exchange is minimal (1-5%), dissolved nutrients accumulate and approach concentrations found in hydroponic solutions.

Total ammonia nitrogen (TAN), the end product of protein transformation, includes two forms: un-ionized ammonia (NH_3) and ionized ammonia (NH_4^+) (Cristea et al., 2002). The un-ionized form of ammonia is extremely toxic to the majority of fish species. The proportion of un-ionized ammonia in TAN is dependent on the pH and temperature of the water. For example, at a pH of 7.00, most of the TAN is in the ionized form, whereas at a pH of 8.75, over 30% of the TAN is in the un-ionized form. Special attention must be given to the efficiency of the biological filter in recirculating aquaculture systems that use saltwater compared to those that use freshwater, as the former operate at a pH between 8.0 and 8.2, while the latter operate around a pH of 7.0.

The lethal concentration of ammonia nitrogen is well-known for many aquaculture species, and literature indicates that the concentration of un-ionized ammonia in the water of a culture tank should not exceed 0.05 mg/l.

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Article

THEORETICAL AND EXPERIMENTAL RESEARCH REGARDING THE VERIFICATION OF MACHINES FOR COMBATING EXISTING DISEASES AND PESTS WITHIN THE FARM "CĂRUNTU C. GHEORGHE" INDIVIDUAL ENTERPRISE FROM THE TOWN OF GIARMATA, JUD. TIMIS

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Abstract: Over the past 30 years, technical inspection of plant protection equipment in use has been introduced in various Member States. This development has been driven by public scepticism about the potential dangers and the need to reduce the consumption of plant protection products. The three main reasons (causes) for inspecting plant protection equipment are: the safety of the personnel carrying out the inspection (EEC Directive 89/655, including the amendments to EU Directive 95/63, concerning the use of work equipment, which contains minimum provisions that can be supplemented by national rules); reducing the risks of environmental pollution by plant protection products; optimal plant protection by applying a minimum amount of plant protection products. Given the primacy enjoyed by the issue of environmental protection, it is assumed that European standards will be increasingly accepted and, implicitly, the measures for testing, approval and technical inspection of sprayers will be extended. Checking sprayers, both old and new, must be carried out constantly, because certain malfunctions can lead to excessive pollution of the environment, water, soil and air, to the allocation of an additional amount of money for chemical solutions (insecticides, pesticides, fungicides) due to the possibility of nozzle orifices wearing out over time, as well as to certain overlaps during work.

1. Introduction

In modern agriculture, protecting crops against diseases and pests is a constant challenge for farmers. Therefore, the application of phytosanitary treatments has become almost an obligation, whether we are talking about large-scale agriculture or just in your own garden.

The fight against diseases and pests in agricultural, fruit and viticultural farms, including the fight against weeds in agricultural crops, is carried out in almost all cases (90% of the treatments applied) mechanized, by spraying, with the help of spraying machines [1-3].

Since the world's population is growing significantly, and agricultural areas are increasingly smaller at the expense of areas with buildings, farmers must obtain the same or even larger harvests on increasingly smaller areas. This cannot happen if the best possible protection of crops is not achieved, which is only achieved with high-performance plant protection machines and with spraying solutions (insecticides, pesticides) that are effective [4-6].

Recently, the concept of cost reduction has been increasingly discussed, and this can be achieved through various possibilities to reduce costs and optimize processes up to 5% more yield, 50% less fuel and 60% less operational time.

For spraying field crops, the most common type of spraying machine is the type carried on the hydraulic system of the general-purpose tractor. These are machines with a tank capacity of between 300 – 1500 [l], sufficient liquid quantity to spray an area of 1 – 5 - 7 [ha], with a single filling [7-9].

In large farms, trailed spraying machines are mainly used. They differ from the mounted ones in that the machine has its own running gear (axle with wheels). These are high-capacity machines (tank capacity 2500 – 6000 [l]). At the same time, they also have high productivity, having a working width of 20 – 48 [m].

Also on large areas, but especially service companies, use self-propelled spraying machines. These machines have their own running gear and engine to drive the spraying equipment and move on the ground. The productivity of these machines is also high, comparable to that of trailed spraying machines, having similar constructive parameters [10,11].

2. Materials and methods

The determinations regarding the verification of the spraying machines were made in the CARUNTU C. GHEORGHE INTREPRINDERE INDIVIDUALA Farm, which is located in Giarmata, Timis County, being a family agricultural holding managed by Mr. Caruntu Gheorghe together with his sons Ionut, Cosmin and David. In total, 1000 [ha] are cultivated divided into the following crops: wheat – 50 [%]; rapeseed – 35 [%]; corn – 15 [%]. The determinations were made according to the European standards in the field and the methods currently used in this direction.

Fig. 1 Area where tractors, combines and agricultural machinery are parked while they are not working – Caruntu Farm.

Two spraying machines were taken for the study, namely:

- A trailed spraying machine Beyne Python 4200 l/24 [m] (figure 2);

Fig. 2 Beyne Python 4200 sprayer – Caruntu Farm.

- A BARGAM portable sprayer – 1200 [l]/ 18 [m] (figure 3);

Fig. 3 BARGAM portable sprayer – 1200 [l]/ 18 [m]– Caruntu Farm.

To determine the number of droplets per cm^2 and the diameter of the droplets, we used water sensitive paper from Germany (figure 4) and a ruler from the Spraying Systems company (figure 5).

Fig. 4 Sensitive sheet.

Fig. 5 Spraying Systems ruler.

To determine the number of drops per nozzle, respectively to determine the uniformity of distribution, we used 4 graduated cylinders (figure 6).

Fig. 6 Graduated cylinders – 4 in number.

To determine the flow rate, we used a flow meter and a flow sensor existing in the "Plant Protection Machines" laboratory, as well as a device equipped with a small RAU computer (electronic device) to see the flow rate value on the circuit (figure 7).

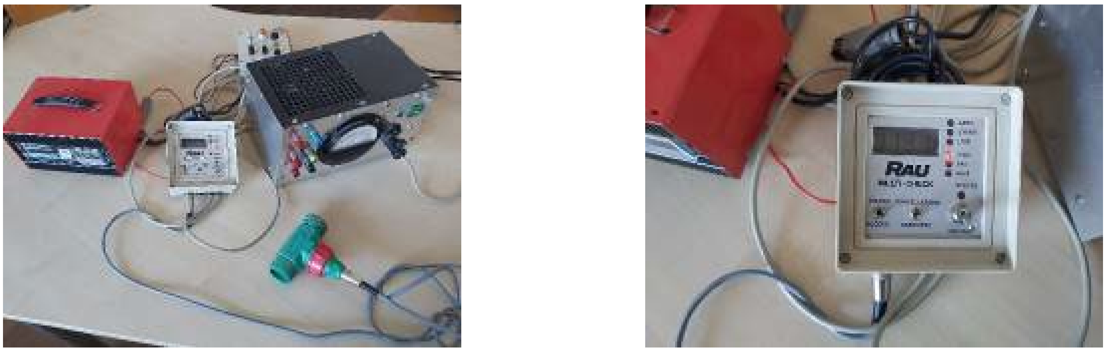

Fig. 7 Flowmeter + flow sensor + Flow measurement device + RAU MULTI-CHECK.

To check the proper functioning of the spraying machine pressure gauge, a pressure gauge from the test kit used on spraying machines produced by Tehnofavorit Bontida was used (figure 8).

Fig. 8 Manometer, original car manometer function check kit.

A tape measure, a 50 [m] long cable on a drum, various classic and tubular wrenches, pliers, different types of nozzles, etc. were also used.

3. Results

At the European Community level, for many years, a European norm has been introduced by which the farmer is obliged to have a check every certain number of years: 1, 2 or 5 years, depending on the country. In England for example, which is no longer currently in the EU, the check is done every year, that is, once every 12 months. In Germany it is done every 2 years. Finally, the farmer receives a sticker that is stuck on the machine, generally on the tank, which allows him to work with that machine for a certain number of years.

In Romania, the legislation was introduced, on paper, in 2012. It specifies that, by 2016, each farmer must have at least one check, after which, the next check should be done after 5 years and then every 2 years. Today we are in 2024 and farmers have not had their sprayers checked on farms in Romania. Why?

The Ministry of Agriculture and Rural Development is in charge of this matter, which imposed that the National Phytosanitary Authority be responsible for this legislation, that is, for the checks on sprayers found in agricultural machinery parks in Romania. We do not know the reasons, but even at present these checks are not officially carried out in Romania, which leads to farmers using sprayers as they please, often leading to environmental pollution with polluting chemicals [12,13].

The checks covered the following:

- checking the flow rate per nozzle;
- checking the uniformity of distribution across the entire working width of the spraying boom;
- checking the pressure gauge;
- checking the nozzles, gaskets, filters and caps;
- checking the flow meter mounted on the machine installation;
- checking the number of drops per [cm2];
- determining the droplet diameter depending on the nozzle.

The checks were carried out both stationary and in the field, in a wheat crop. The machines studied were from the Beyne and Bargam companies.

The Beyne sprayer worked in conjunction with a Finnish Valtra tractor purchased from the MEWI Orțișoara company (figure 9).

Fig. 9 Beyne sprayer in agregate with a Valtra tractor.

The machine is also equipped with an on-board computer, mounted in the tractor cabin, from where certain parameters can be monitored and adjusted such as: working speed, solution flow rate, amount of solution per hectare, etc.

The water supply to the tank was done through a tanker equipped with a tank made of fiberglass (figure 10). This cannot be done directly from a river, lake, well, etc. to avoid spilling chemicals from the spraying machine into the water. International legislation has regulated this through laws.

Fig. 10 Water tank used to fill the solution tank.

The choice of nozzles is made through special software that has been installed on the mobile phone, and this is done according to certain parameters, namely: the amount of solution per hectare, speed of advance and distance between nozzles, which is generally 50 [cm] (figura 11).

Fig. 11 The nozzle selection program installed on the mobile phone.

The flow rate at the nozzles was calculated using several graduated cylinders (figure 12). It was calculated at 15 sec. After which it was multiplied by 4 and the flow rate per nozzle in one minute was determined. The flow rate was calculated for two types of nozzles that are used, namely:

- red nozzle, caliber 04, 3.3 [bar], 200 [l/ha];
- brown nozzle, caliber 05, 2.1 [bar], 200 [l/ha].

Generally, the minimum speed is [10 km/h]. The working speed during the determinations was 14.5 – 15 [km/h].

- brown nozzle, caliber 05, 2.1 [bar], 200 [l/ha].

Generally, the minimum speed is [10 km/h]. During the determinations, the working speed was 14.5 – 15 [km/h].

Fig. 12 Determining the flow rate at the red nozzle.

Table 1

Flow rate obtained on each nozzle for Beyne sprayer – Red nozzle – caliber 04.

Nr. duză	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**
Q [l/min.]	1,72	1,76	1,72	1,68	1,6	1,6	1,52	1,52	1,56	1,6
Nr. duză	**11**	**12**	**13**	**14**	**15**	**16**	**17**	**18**	**19**	**20**
Q [l/min.]	1,56	1,56	1,48	1,56	1,56	1,6	1,36	1,48	1,56	1,56
Nr. duză	**21**	**22**	**23**	**24**	**25**	**26**	**27**	**28**	**29**	**30**
Q [l/min.]	1,52	1,52	1,52	1,56	1,44	1,52	1,44	1,48	1,52	1,52
Nr. duză	**31**	**32**	**33**	**34**	**35**	**36**	**37**	**38**	**39**	**40**
Q [l/min.]	1,52	1,52	1,48	1,48	1,48	1,48	1,48	1,48	1,52	1,52
Nr. duză	**41**	**42**	**43**	**44**	**45**	**46**	**47**	**48**		
Q [l/min.]	1,36	1,40	1,36	1,40	0 – duza înfundată – după curăţire 1,40	1,40	1,44	1,48		

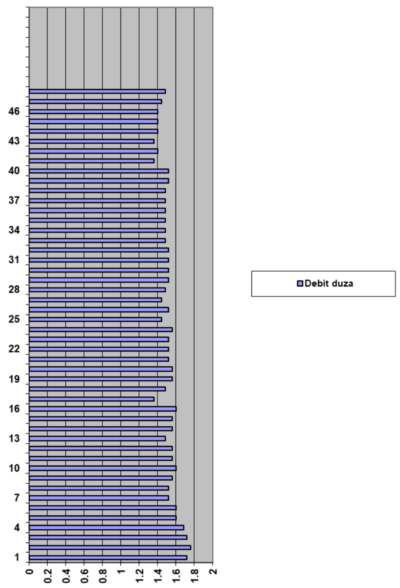

Fig. 13 Uniformity of distribution at red nozzle – Flow rate per nozzle.

At nozzle number 45, the flow rate was initially "ZERO", but after cleaning it with a brush, the flow rate reached 1.4 [l/min.].

Table 2

Flow rate obtained on each nozzle for the Beyne sprayer – Brown color nozzle – caliber 05.

Nr. duză	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**
Q [l/min.]	1,76	1,20	1,76	1,64	2,20	2,16	2,20	2,24	2,16	2,16
Nr. duză	**11**	**12**	**13**	**14**	**15**	**16**	**17**	**18**	**19**	**20**
Q[l/min.]	2,24	2,20	2,52	2,52	2,44	2,48	2,24	2,24	2,20	2,20
Nr. duză	**221**	**22**	**23**	**24**	**25**	**26**	**27**	**28**	**29**	**30**
Q [l/min.]	2,20	2,24	2,24	2,16	2,08	2,16	2,28	2,24	2,40	2,20
Nr. duză	**31**	**32**	**33**	**34**	**35**	**36**	**37**	**38**	**39**	**40**
Q [l/min.]	2,20	2,12	2,24	2,20	2,24	2,24	2,28	2,36	2,32	2,32
Nr. duză	**41**	**42**	**43**	**44**	**45**	**46**	**47**	**48**		
Q [l/min.]	2,24	2,24	2,20	60- duza înfundată – după curăţire 2,32	2,36	2,12	2,24	2,16		

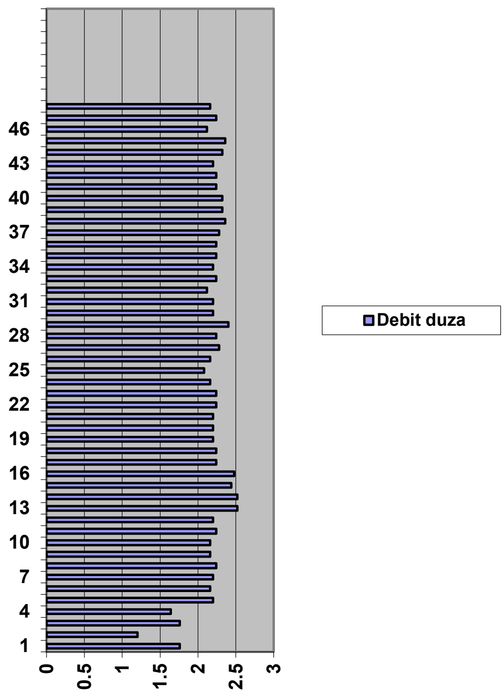

Fig. 14 Distribution uniformity at the brown nozzle – Flow rate per nozzle.

At nozzle number 44, the initial flow rate was 0.24 [l/min.], but after cleaning it with a brush, the flow rate reached 2.32 [l/min.].

For the field measurements, the tractor-sprayer unit was moved to a soil cultivated with wheat, in transport position. In the first phase, the unit was prepared for spraying, the boom moving from the transport position to the working position (opening the boom) by simply pressing a button in the tractor cabin. This was achieved by a hydraulic system equipped with hydraulic cylinders. For field work on the farm, technological paths are used as can be seen in figure 15.


Fig. 15 Sola cultivated with wheat and technology paths.


Fig. 16 Machine ready for spraying.

The installation of sensitive leaves in the field crop was done both at the level of the upper leaves and at the level of the soil, i.e. on the soil. They were attached to the leaves by means of clips.


Fig. 17 Sensitive leaves caught in the wheat field.

Fig. 18 Beyne sprayer in field operation and determination of the number of drops per square centimeter.

The sheets, after being manually collected, were stapled onto sheets of paper, taking into account the working width of the ramp (figure 19).

Fig. 19 The leaves obtained from spraying with the red nozzle, at ground level.

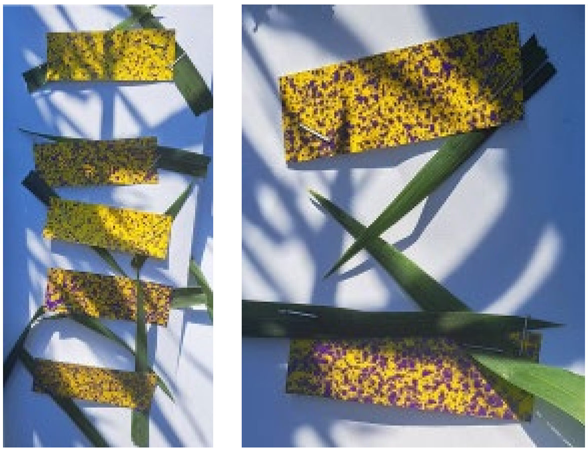

Fig. 20 The leaves obtained by spraying with a red nozzle, at the level of the upper leaves.

The determination of the number of drops per cm^2, the diameter of the drops and the spraying range according to the European standard in the field was done using the ruler from Spraying Systems Co. and a graduated ruler (figure 21).

Fig. 21 Determining the number of drops per cm² with the Spraying Systems ruler in the case of the Beyne machine.

After the measurements, the following results were obtained:

- At the red nozzle of caliber 04 - soil level: 50 [drops/cm^2] - 20 drops with a diameter of 500 [μm] + 30 drops of 1000 [μm] - we have a coarse to very coarse spray;
- At the brown nozzle of caliber 05 - soil level: 70 [drops/cm^2] - diameter between 150 - 500 [μm] - we have a medium to coarse spray;
- At the red nozzle of caliber 04 - leaf level: 150 [drops/cm^2] - 50 drops with a diameter between 50 - 150 [μm] = 100 drops with a diameter of 300 [μm] - we have a very fine + fine to medium spray;
- At the brown nozzle of caliber 05 – leaf level: 50 drops with a diameter between 500 – 1500 [μm] – 30 drops with a diameter between 500 – 1000 [μm] + 20 drops with a diameter between 1000 – 1500 [μm] – we are dealing with a very coarse spray towards rain.

After measurements taken on the Bargam spraying machine at the leaf level, the following results were obtained:

- At the red nozzle of caliber 04: 70 [drops/cm^2] with a diameter ranging from 300 – 1000 [μm] – 40 drops with a diameter ranging from 300 – 500 [μm] + 30 drops with a diameter ranging from 500 – 1000 [μm] – here we are dealing with a coarse to very coarse spray.
- At the gray nozzle of caliber 06: 180 [drops/cm^2] with a diameter ranging from 5 – 150 [μm] – 100 drops with a diameter ranging from 5 – 50 [μm] + 80 drops with a diameter ranging from 100 – 150 [μm] – here we are dealing with a very fine to fine spray.

The flow rate on the system is checked using a flow meter, equipped with 2 propellers and a flow sensor, mounted on the working circuit. Its verification is imperative in order to be able to see the set flow rate every second, which is currently done using a computer mounted in the tractor cabin.

Over time, this flow meter can break down, deteriorate, which leads to the replacement of the entire flow meter or just the flow sensor if only it is broken.

To check the machine's flow meter, we used another flow meter that was previously tested in the laboratory. We dismantled the original flow meter mounted on the spraying machine and mounted another flow meter. We checked using a special device that is in the equipment of the "Plant Protection Machines" laboratory, both the flow rate obtained using the original flow meter and the flow meter from the verification kit. The values obtained were the same, so the machine's flow meter is working properly. The flow rate was checked for both flow meters and on the computer specially mounted in the tractor cabin, its value being the same for both, so the machine's flow meter is operating within normal parameters.

Fig. 22 Preparation and installation of the flow measurement equipment at the two flow meters.

4. Discussion

The studies regarding the verification of the spraying machines that are in the farm equipment of "CĂRUNTU C. GHEORGHE" INTREPRINDERE INDIVIDUALĂ from Giarmata, Timiş County were carried out in compliance with the European norms in the field.

The farm currently owns 3 spraying machines, two being towed and one self-propelled. The verifications were carried out on the Beyne and Bargam towed machines. The self-propelled spraying machine is the variant of the German company Fendt.

The verifications aimed at: checking the nozzles and seals, determining the flow rate on each nozzle, the uniformity of the solution distribution, checking the accuracy of the pressure gauge, checking the flow meter, determining the number of drops per cm2, determining the form of spraying (dispersion) of the sprayed liquid depending on the diameter of the drops.

Checking the flow rate at the spray nozzles led to the conclusion that, for the most part, it corresponds to its initial values, but there were also situations when it was too high or too low. If the nozzle flow rate was very low, even close to "zero", the nozzle was cleaned. After cleaning them, new determinations were made, and the values reached the desired ones. If the flow rate was high or even very high, it was recommended to change the respective nozzles.

All the spray nozzle gaskets on the two spray machines were checked, and they were unused and suitable for quality spraying. Only one gasket had problems and this was changed.

5. Conclusions

A problem that we consider unacceptable is the fact that filters were not used on the nozzles, which will eventually lead to premature wear of the nozzles and their replacement after a short period of operation.

On the Beyne sprayer, after the measurements taken, the following results were obtained:

- at the red nozzle of caliber 04 - soil level: 50 [drops/cm^2] - 20 drops with a diameter of 500 [μm] + 30 drops of 1000 [μm] - we have a coarse to very coarse spray;
- at the brown nozzle of caliber 05 - soil level: 70 [drops/cm^2] - diameter between 150 - 500 [μm] - we have a medium to coarse spray;
- at the red nozzle of caliber 04 - leaf level: 150 [drops/cm^2] - 50 drops with a diameter between 50 - 150 [μm] = 100 drops with a diameter of 300 [μm] - we have a very fine + fine to medium spray;
- at the brown nozzle of caliber 05 – leaf level: 50 [drops/cm^2] with a diameter between 500 – 1500 [μm] – 30 drops with a diameter between 500 – 1000 [μm] + 20 drops with a diameter between 1000 – 1500 [μm] – we are dealing with a very coarse spray towards rain.

At the Beyne spraying machine, equipped with nozzles of caliber 04-red and 05-brown, the spray is from medium to coarse and very coarse at the leaf level at the ground level. At the leaf level things change: at the red nozzle we have a very fine spray towards medium, and at the brown nozzle we have a very coarse spray towards rain.

On the Bargam spraying machine, after measurements taken at the leaf level, the following results were obtained:

- at the red nozzle of caliber 04: 70 [drops/cm^2] with a diameter ranging between 300 – 1000 [μm] – 40 drops with a diameter ranging between 300 – 500 [μm] + 300 drops with a diameter ranging between 500 – 1000 [μm] – here we are dealing with a coarse to very coarse spray;
- at the gray nozzle of caliber 06: 180 [drops/cm^2] with a diameter ranging between 5 – 150 [μm] – 100 drops with a diameter ranging between 5 – 50 [μm] + 80 drops with a diameter ranging between 100 – 150 [μm] – here we are dealing with a very fine to fine spray.

On the Bargam sprayer, the spraying at the leaf level is coarse to very coarse with the red nozzle, and very fine to fine with the gray nozzle.

After quite thorough checks in the field, it was observed that with each spraying we encounter fine and very fine drops on 1 cm^2 or 1 m^2 combined with coarse to very coarse drops, even going towards rain.

By changing the sprayer flowmeter and replacing it with a flowmeter from the verification kit, the final result was the same value as that obtained with the original flowmeter, which could be seen both on the BRAVO computer of the sprayer and on the RAU computer from the verification kit mounted on the sprayer.

The machine's pressure gauge works within normal parameters, this being checked with another "glycerine" type pressure gauge existing in the verification kit.

It is recommended that every year (for example in England) or at least every 2 years (for example in Germany) a check of the spraying machine be carried out, even if at present this is not yet mandatory in Romania. This can even be done by the farmer by purchasing graduated cylinders, a spare flow meter, a spare pressure gauge, etc.

It is recommended that in the future filters be used on the nozzles to avoid their premature wear.

It is recommended that the nozzles be checked after each spraying. If they are clogged, they should be cleaned, and if they are worn, they should be changed.

The farmer can even go further with these checks and purchase sensitive sheets from nozzle manufacturers on the market and determine for himself the number of drops per cm2, their diameter and the type of dispersion of the sprayed liquid in accordance with European legislation in the field.

It is recommended that farmers purchase a ruler to determine the type of nozzle they will be working with. The calculation formulas have been replaced with very practical and easy-to-use rulers. These rulers are made by nozzle manufacturers, namely: Lechler, Agrotop, Teejet, Albuz, etc. With their help, depending on the quantity distributed per hectare and working speed, the flow rate at the nozzle is determined and the appropriate nozzle (suitable) for the “x” crop is chosen.

It is recommended that in the future, the attachment of sensitive leaf blades be done at all levels, i.e., top, middle and bottom. Of course, this requires more envelopes with sensitive leaves, i.e. more money. But, by doing this, we can see the coverage on all 3 levels of the plant. Usually, the most drops fall on the top of the leaves, fewer drops in the middle, and the fewest drops reach the bottom level.

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Article

COMPARATIVE EVALUATION OF THREE MULCHING TECHNIQUES IN ORGANIC AGRICULTURE, ANALYZING ANNUAL COSTS AND THE IMPACT ON SOIL QUALITY

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Abstract: Organic farming offers a sustainable approach to agriculture, aiming to enhance crop production while preserving ecological balance and ensuring food safety. However, a significant challenge in organic systems is the reliance on intensive soil tillage for weed control, which can degrade soil quality over time and increase vulnerability to erosion by wind and water. Mulching presents a viable, eco-friendly alternative, improving soil health and offering economic benefits by lowering the costs of crop establishment and maintenance—particularly critical for organic farms. This study evaluates and compares the economic and agronomic impacts of three widely used mulching methods, focusing on their effectiveness in managing both main and cover crops.

1. Introduction

Given the challenges of feeding a growing global population, it is imperative to develop sustainable agricultural practices that increase crop yields and maintain their ecological integrity. In this context, organic agriculture in line with conservation agriculture is a strategy for achieving sustainable goals.

Problems with organic farming arise from the over-cultivation of soil to suppress weeds. This approach compromises soil health and quality and increases exposure to water and wind erosion [1]. On the other hand, the no-till (NT) practices proposed by conservation agriculture have a number of advantages (reducing soil erosion, labor costs and energy consumption), but the adoption of NT in organic farming remains difficult to achieve due to problems related to weed management [2]. Despite the advantages of NT in terms of soil conservation opportunities, the correlation between herbicide use and NT raises concerns for the development of herbicide resistance, as well as undesirable effects on the environment and biodiversity [3].

Integrated weed management that encompasses other cultural, biological, and mechanical controls has potential and needs to be incorporated into organic research efforts for zero-tillage farming [4].

Until the 1940s, in fact, agriculture was organic in its early days before the development and use of synthetic fertilizers and pesticides. Advances in plant genetics, agricultural equipment, and other scientific and technological advances suggest that modern organic agriculture represents a major improvement over earlier versions. Even so, the principles underlying agricultural practices prior to the 1940s continue to guide organic farmers today [5-6].

Adopting no-till mulching is an interesting strategy for more and more farmers, as it brings benefits to soil quality, is economically viable by reducing fuel and labor consumption, especially in organic farms and beyond [7-8]. The main challenges in organic farming are the management of weeds and cover crops while maintaining optimal production. The challenges are fueled by the lack of knowledge, skills and equipment needed to optimize the establishment of cover crops and their efficient completion to obtain profitable main crops [9-10].

The main threat to agricultural productivity worldwide is soil degradation. The use of mulching by applying or retaining crop residues in the field is a necessity to prevent soil erosion and maintain soil quality in optimal parameters in order to improve crop productivity [11-14]. Mulching is the common practice of applying materials (plastic, crop residues, manure, sand, etc.) to the soil surface before, during or immediately after planting [15].

Mulch is divided into two categories, organic and inorganic. Organic mulch is commonly used due to its natural biodegradability [16]. Inorganic mulch comes in several types (gravel, polyethylene plastics, etc.). In agriculture, mulch is mainly used to control soil erosion and to optimize soil moisture and temperature, thus favoring crop yield. [17-19]. In addition, organic mulch materials (crop straw, grasses, sawdust, etc.) improve soil quality, i.e. physical, chemical and biological properties by supplementing the supply of organic matter to the soil during the decomposition process and positively influences earthworm biomass [20-21]. It has been reported that straw improved soil fertility and has a rich content of mineral elements (macroelements nitrogen (N), phosphorus (P), potassium (K)) and organic carbon content [22]. Also, long residues used as mulch have a fertilizing capacity waste bigger TO END SEASON of vegetation compared to WASTE short, without effect HARMFUL on EFFICIENCY culture [23].

Another important soil parameter is the carbon content, which is why, through various soil practices (including mulching), it is feasible to increase soil organic matter and then soil carbon content, considered one of the main elements of soil quality [24-25]. The increase in soil organic carbon stock occurs as a result of a positive relationship between C input (aboveground and belowground biomass) and C output (heterotrophic soil organisms and soil erosion) [26].

Soil quality is the ability of a soil to function within an ecosystem, support biological productivity, maintain environmental quality, and promote plant and animal health [27]. Soil quality results from beneficial effects that are reflected in an improvement in soil organic carbon in the top 10 cm of soil. [28]. Soil quality also produces improved water infiltration ratio , improved water retention capacity, lower bulk density, greater aggregate stability, and better soil structure [29-31].

While some scientific studies highlight certain drawbacks of mulching, these concerns are often not reflected under real field conditions, where such disadvantages rarely pose a threat to soil health or crop development. Overall, the benefits of mulching prevail, as it serves as a cost-effective method for weed suppression and significantly contributes to soil moisture conservation [32].

The aim of this paper is to evaluate the common mulching methods applied to fruit trees, considered economically suitable for organic farming. The costs required for the establishment and maintenance of both the main crops and the cover crops were evaluated. In this context, the benefits that each evaluated mulching method can bring regarding the improvement of soil quality by maintaining optimal moisture and temperatures, carbon capture in the soil, thus supporting the sustainability and biodiversity of the ecosystem, as well as the disadvantages of each mulching method were considered.

2. Materials and methods

2.1. Associated works on each mulching method

The mulching methods were tested on experimental plots within INMA Bucharest. The average rainfall for Bucharest, Romania is 550-600 mm per year. The soil in this location is reddish-brown, consisting of exclusively Quaternary deposits represented by loess and loessoid deposits.

The experiment was initiated in the spring of 2021 and ran for a period of 3 years until the summer of 2024. The crops used in the project were from the shrub category, namely the raspberry *Rubus idaeus,* a member of *the Rosaceae Juss. family, the genus Rubus* ; the Siberian blueberry or *Lonicera caerulea var. kamtchatica* and the blackberry *Rubus spp.*

When establishing the crops, the possibility of mechanized work was taken into account, which is why the spaces between the rows were taken at approximately 2.40 m, while the cultivated and mulched row has a width of 0.70 m for all crops. The length of the rows was 70 m/row. The total area of the plot that was the subject of the study was 2600 m², and on each experimental plot the area was 650 m².

Given that the three crops used in the project belong to the shrub family, which require deep soil mobilization, when establishing the crops, the soil work was preceded by plowing with the T50 tractor and plow. The land preparation for planting was carried out with the T50 tractor and agriculture combine. The same equipment was also used to prepare the land for sowing, in the spaces between the rows of the blueberry crop, where lucerne *(Medicago sativa) was sown* as a cover crop. Subsequently, the soil work was minimized by applying various types of mulch and cover crops, precisely in order to reduce interventions on the soil as much as possible and benefit from the advantages of soil conservation.

Mulching was applied during the same period on the three experimental plots and three different mulching methods were applied (fig. 1).

Figure 1. Experimental plots comprising different types of mulching

- ***Applying mulch from plant residues***

  The application of chopped plant residues was performed manually. The chopped plant residues resulted from processing with the T80+Skorpion 160R tractor (special equipment for chopping woody plant residues) from branches from various trees and ornamental shrubs, resulting from seasonal pruning carried out within the institute (fig.2).

Figure 2. The chopping process of vegetable waste

Figure 3. Mulching from plant residues in the culture of Siberian blueberry (***Lonicera caerulea var. Kamtchatica)***

➢ ***Applying paperboard mulch***

The paper cardboard mulch came from the packaging of various equipment purchased by the institute and usually stored in a specially arranged place for later recycling. The application was done manually. In both the case of the mulching method using plant residues and the case of the mulching method using paper cardboard, a cover crop of alfalfa *(Medicago sativa) was grown* in the spaces between the rows, which was subsequently mowed with a Bertolini AGT140 brushcutter and left on the ground as mulch. The main crop on which the two mulching methods were applied was Siberian bilberry *(Lonicera caerulea var. kamtchatica)* .

Figure 4. Paperboard mulching for Siberian blueberry (***Lonicera caerulea var. Kamtchatica) cultivation***

➢ ***Applying fabric mulch***

The mulch was applied mechanically with a T50 tractor + special equipment for spreading the mulch film and consisted of purchasing a textile mulch film specially designed for applying mulch to crops. In this case, no cover crop was grown in the spaces between the rows, and maintenance work was carried out mechanically. The textile mulch film was applied to the raspberry crop *(Rubus idaeus).*

Figure 5. Textile film mulching for raspberries ***(Rubus idaeus)***

➢ ***No mulch application (control)***

In the experiment on one of the four plots, no mulching method was used on the blackberry crop *(Rubus spp.)* . Also, no cover crop was grown in the spaces between the rows, precisely to observe the differences between the plots where mulching/cover crop methods were used and the plot where no mulching/cover crop method was used.

Figure 6. No mulching in blackberry *(Rubus spp.) cultivation*

2.2. Cost calculation methods

The management applied to the experimental plots was accounted for in order to have an idea of the financial costs involved in the strategy of the mulching methods chosen. The costs of soil work were analyzed, which consisted of plowing and land preparation work for planting in the case of raspberry, blueberry and blackberry crops and sowing for the cover crop (alfalfa) in the spaces between the rows of the Siberian blueberry crop. The mulch application work was also analyzed, which consisted of spreading the textile mulch film on the raspberry crop, as well as spreading plant debris on the Siberian blueberry rows. Here, we also took into account the weed maintenance work carried out between the spaces between the rows of the raspberry and blackberry crop where no cover crop was used.

➢ ***Ground works fuel costs***

The standard fuel consumption of the machine (T50 tractor) in different tasks and types of work mentioned above was taken into account. For plowing, the standard consumption is 25l/ha, for soil preparation and crop maintenance 5l/ha and for film spreading 4l/ha. These values were correlated with the experimental plot area to find out the fuel costs as follows:

- the total area of the experimental plots is 2600 m², respectively 650 m² /experimental plot;
- price of fuel was set at 1.5 euros/liter for diesel according to the average fuel prices at gas stations;

- fuel consumption was calculated for an experimental plot of 650 m², resulting in a cost of 2.44 euros for plowing;

The same calculation was made for the land preparation works for planting/sowing, respectively for the application of textile foil to the raspberry plantation and plant residues to the Siberian blueberry plantation.

➢ ***Fuel costs for processing vegetable waste***

The shredding of vegetable residues was carried out using the T80 tractor + Skorpion 160R shredding equipment.

- it was calculated for 3 rows, each 70 m long where a 10 cm layer of plant residues will be applied, the result being 14.70m³ necessary for applying plant residues to the Siberian blueberry crop;
- the fuel consumption of the T80 tractor for this type of load was taken into account, namely 6l/h;
- the efficiency of the Skorpion 160R plant waste processing equipment is established by the manufacturer, namely 12m³/h;
- the operating time of the Skorpion 160R chopping equipment was calculated, resulting in 1.2 h to obtain the required quantity;
- the fuel consumption was calculated for the cost of processing vegetable waste, the result being 10.80 euros.

➢ ***Fuel costs for mowing cover crops***

For mowing alfalfa (cover crop in the space between the rows of crops mulched with plant debris and paper cardboard), the Bertolini AGT140 lawn mower was used.
- for the periodic mowing of the alfalfa cover crop, the consumption given by the manufacturer was taken into account, namely 2.5 l/h.
- During the 3-year study period, 12 mowings were performed. The time allocated for each mowing was approximately 1 hour;
- the fuel price was set at 1.4 euros/liter for gasoline according to the average fuel prices at gas stations;
- the cost of fuel consumption for mowing the cover crop was calculated, resulting in 42.00 euros.

➢ ***Crop irrigation costs***

When calculating irrigation costs, the consumption given by the manufacturer of 4l/h per 100 m of tube was taken into account. For a more accurate calculation related to the studied area, the consumption per meter of the drip system was found by calculating as follows:
- the irrigation period between June and September was calculated and the irrigation time expressed in hours for each month according to the needs of the crops, the result was 306 h/year of irrigation time for Siberian blueberry crops (mulching with plant residues) and raspberry crops (mulching with textile foil), respectively 918 h/year for blackberry crops (without mulching) and Siberian blueberry (mulching with paper cartons).

To determine the irrigation costs of the studied crops, the following calculations were performed:
- consumption was calculated for the experimental lots having 210m length/exp. lot, resulting in 8.40 l/h ;
- the irrigation time allocated to each experimental lot was calculated, resulting in a quantity of 1285.40 l for the Siberian blueberry crop (vegetable residue mulching) and the raspberry crop (textile film mulching) and 3855.60 l for the blackberry crop (without mulching) and Siberian blueberry (paper cardboard mulching).

- using the values in cubic meters, the irrigation costs for the 4 lots were calculated (1.81 euros/year for the lots mulched with plant residues and textile foil, respectively 5.40 euros/year for the control lot and the lot mulched with cardboard).

each experimental batch was calculated for 3 study years, resulting in:
- 5.43 euros (lot of mulching plant residues)
- 5.43 euros (textile foil mulching lot)
- 16.20 euros (lot without mulch)
- 16.20 euros (paper cardboard mulching lot)
- The total amount is <u>43.26 euros (crop irrigation cost)</u>

2.3. Soil samples

Soil sampling and measurements were carried out simultaneously during the 3 years of study in the Siberian blueberry crop where mulching with plant residues and paper cardboard was applied, in the raspberry crop where textile foil was used and in the blackberry crop where no mulching method was applied and consisted of:

- ***Humidity measurement***

The measurement was performed using the Extech MO750 moisture meter, a soil moisture measuring device in the range of 0-50%. The instrument is equipped with a min/max function that allows recording both minimum and maximum values, a HOLD function to maintain the measured value on the screen and a stainless steel probe whose length is 200 mm.

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Figure 7. Humidity measurement

- ***Compaction measurement***

Compaction measurement was performed using a soil compaction measurement instrument, namely the Fieldscout SC 900 with accuracy: ± 0.5 in (1.25 cm) depth, ±15 PSI (103 kPa) pressure, Measurement range: 0 to 18 inches (0 to 45 cm), 0 to 1,000 PSI (0 to 7,000 kPa) and data logger capacity: 772 profiles without GPS; 579 profiles with GPS.

The usefulness of measuring compaction can be directly influenced by the application of different mulching methods. This results from the fact that the soil represents the plant's water, nutrient and oxygen reservoir. For this reason, soil with a high degree of compaction has fewer pore spaces to retain what the plant needs. A compacted soil prevents moisture penetration, decreases the assimilation of nutrients, creates unfavorable conditions for the development of the root system and leads to the development of anaerobic microbes. Significant production losses can occur due to compaction.

Figure 8. Compaction measurement

3. Mulch decomposition monitoring

Paper cards year 1 | Paper cards year 2 | Paper cards year 3

Figure 9. Monitoring the decomposition of paper cardboard mulch

Plant residues year 1 Plant residues year 2 Plant residues year 3

Figure 10. Monitoring the decomposition of mulched plant residues

Textile foil year 1 Textile foil year 2 Textile foil year 3

Figure 11. Monitoring decomposition of mulched plant residues

4. Results

4.1. Cost results of mulching methods

Table 1 Cost evaluation for the tested mulching methods

Type of work	Number of works/ year	Number of papers 2021-2024	Equipment/Materials used	Supply			Mulching Plant debris (Blueberry = 0.065 ha)		Mulching Cardboard paper (Blueberry = 0.065 ha)		Textile film mulching (Raspberry = 0.065 ha)		Without mulching (Blackberry = 0.065 ha)	
				Power supply type	Consumption rate (l/ha; *m³/h; **l/h)	Fuel price (liters) / water (m³) (euro)	Fuel/water consumption (l/ha; **l/h)	Fuel cost/ Other expenses (euro)	Fuel/water consumption (l/ha; **l/h)	Fuel cost/ Other expenses (euro)	Fuel/water consumption (l/ha; **l/h)	Fuel cost/ Other expenses (euro)	Fuel/water consumption (l/ha; **l/h)	Fuel cost/ Other expenses (euro)
Plowing the soil	1	1	T50+plow	motorină	25	1,5	1,625	2,44	1,625	2,44	1,625	2,44	1,625	2,44
Planting/sowing soil preparation	1	1	T50+combinator	motorină	5	1,5	0,325	0,49	0,325	0,49	0,325	0,49	0,325	0,49
Textile foil application	1	1	T50+special equipment	motorină	4	1,5	-	-	-	-	0,256	0,38	-	-
Chopped vegetable scraps	1	1	T80+Skorpion160R+manual	motorină	*12 /**6	1,5	**7.20	10,80	**3.00	4,50	-	-	-	-
Application of plant residues	1	1	T50+tow+manual	motorină	2,5	1,5	0,160	0,24	-	-	-	-	-	-
Paper cardboard application	1	1	manual	-	-	-	-	-	-	-	-	-	-	-
Plantation	1	1	manual	-	-	-	-	-	-	-	-	-	-	-
Cover crop sowing	1	1	T50+seeder	motorină	4	1,5	0,256	0,38	0,128	0,19	-	-	-	-
Cover crop mowing	4	12	Brushcutter Bertolini AGT140	benzină	**2,5	1,4	**15.00	21,00	**15	21,00	-	-	-	-
Weed maintenance work	6	18	T50+combinator	motorină	5	1,5	-	-	-	-	1,950	2,93	3,900	5,85
Foil purchase	1	1	-	-	-	-	-	-	-	-	-	159,60	-	-
Irrigation system purchase	1	1	-	-	-	-	-	42,00	-	42,00	-	42,00	-	42,00
Irrigation system consumption	1224 h	3672 h	Drip system	apă	**4	1,4	**8,40	5,43	**8,40	16,20	**8,40	5,43	**8,40	16,20
Total costs								**82,78**		**86,82**		**213,27**		**66,98**

* calculation in m³/h ; ** calculation in l/h

4.2. Mulched crop moisture results

Table 2 Moisture content in soil

Nr. crt.	Blackberry (without mulch) %	Siberian bilberry (vegetable waste) %	lucerne (intercalated) %	Raspberry (fabric foil) %
Year 1	15,6	**20,5**	14,8	21,2
Year 2	16,4	24,1	15,9	24,8
Year 3	17,1	25,4	16,7	25,9
Multiannual average	**16,37**	**23,33**	**15,8**	**23,97**

4.3. Soil compaction results of mulched crops

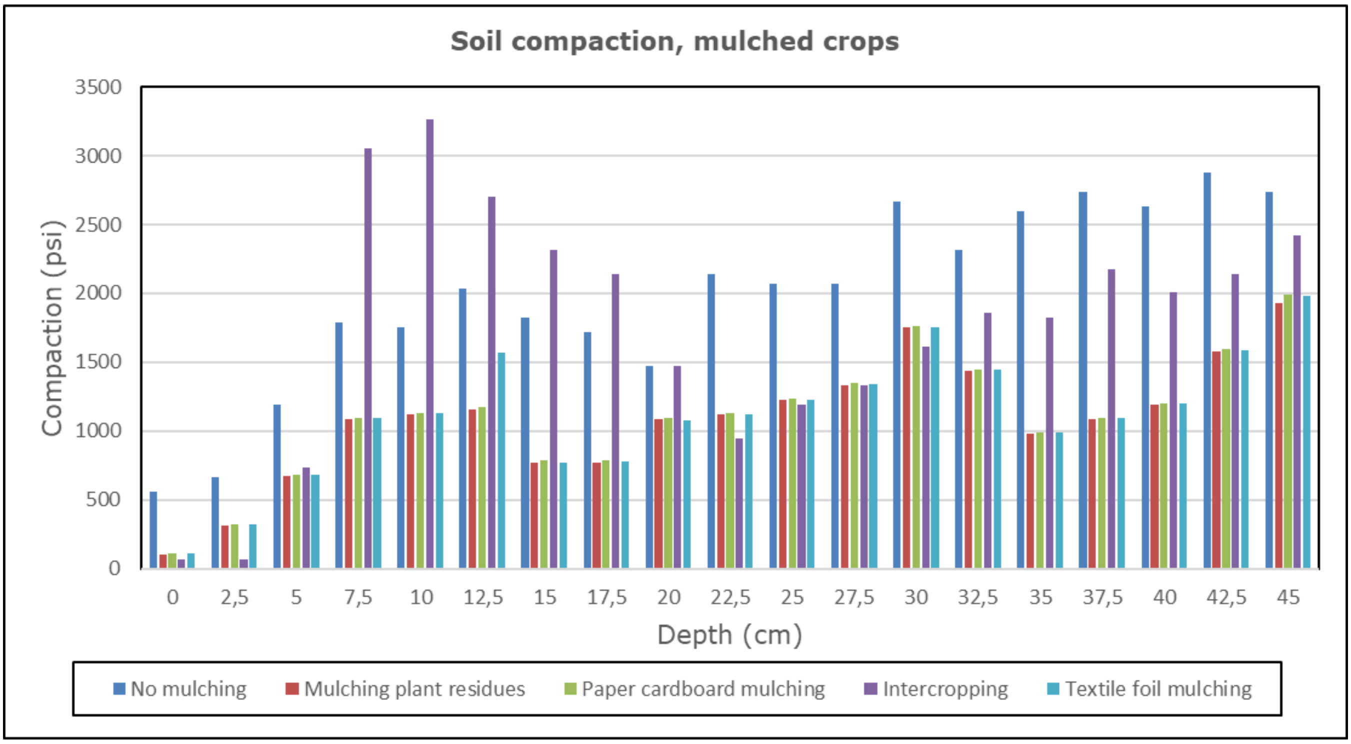

Figure 12. Soil compaction graph

5. Conclusions

The most expensive mulching method turned out to be mulching with textile foil worth 2 13.26 euros. The additional costs compared to the other methods consisted of the purchase of the foil and those related to the fuel consumption for stretching the foil, to which are added the costs necessary for maintenance work in the spaces between the rows. In the 3 years of study, the foil did not show significant damage.

The other mulching methods had similar values in terms of costs, mulching with plant residues 82.77 euros and 86.83 euros for mulching with paper cardboard. In the case of these mulching methods, an intercrop of alfalfa was cultivated in the spaces between the rows. Usually, between January and April, alfalfa grew to a height of 55-60 cm, at which point it negatively influenced the main crop, whose height coincided with that of alfalfa. Therefore, at this time it is necessary to carry out the activity of mechanized cutting of alfalfa (intercropped cover crop).

During the 3 years of study, the plant debris partially decomposed. The most significant damage due to decomposition was observed in year 3 when small areas began to appear through which weeds appeared next to the main blueberry crop. Another problem was the appearance of rodents that made holes in certain areas in the plant debris layer.

In the case of mulching with paper cardboard decomposition was much more pronounced. This had effects from the first year onwards in the sense that areas appeared where weeds appeared especially towards the end of the vegetation period of the main blueberry crop without significant damage to it. In contrast, from year 2 onwards the decomposition was evident, and the paper cardboard mulch was no longer able to suppress weed growth except to a small extent. From year 3 onwards the paper cardboards decomposed completely. Another problem was the wind which during the study sometimes uncovered certain areas mulched with cardboards.

In areas mulched with textile foil and plant debris, the humidity was relatively higher, which led to a reduction in the water consumption necessary for irrigation and optimal crop development.

The degree of compaction was higher in the alfalfa intercrop in the measured range 7.5-20 cm and in the unmulched crop between 0-5 cm and 22.5-45 cm. In the mulched crops, the values were close, but lower in the measured range 0-45 cm compared to the unmulched/intercropped crop.

Of the 3 methods used, we consider that the method with plant residues (chopped from the branches of trimmed trees) along with the use of an intercrop in the space between the rows (alfalfa) presents an important cost/benefit ratio resulting from improving soil quality, supporting biodiversity and solving environmental problems related to waste disposal.

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Article

THE POSSIBILITY OF USING WOOL WASTE IN AGRICULTURE

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Keywords: *waste-wool, hydrolysate, biofertilizer.*

Abstract: Conserving and/or increasing soil fertility in agriculture, primarily through its organic content, improves agricultural production. Organic compounds with fertilizing action applied on agricultural lands bring real positive effects in the development of plants and increase the quality and quantity of agricultural production considering the fact that they help to improve and maintain the physico-chemical and structural characteristics of the soil and thus, to increase its productive potential. Also, these compounds stabilize and facilitate the absorption by plants of macro- and microelements from the soil, which leads to the intensification of biological processes in the soil and plants, reduce the loss of mineral nutrients from the soil through leaching or chemical reactions that lead to nitrogen loss and reduce soil toxicity by complexing heavy metals. Organic compounds with fertilizing action applied on agricultural land bring real positive effects in the development of plants and increase the quality and quantity of agricultural production considering that they help to improve and maintain the physico-chemical and structural characteristics of the soil and thereby, to increase its productive potential. It also stabilizes and facilitates the absorption by plants of macro and microelements from the soil, which leads to the intensification of biological processes in the soil and plants, reduces the loss of mineral nutrients from the soil through leaching or chemical reactions that lead to nitrogen loss and reduces toxicity the soil by the complexation of heavy metals. Wool as a biomaterial is rich in nitrogen due to its amide groups and possesses a moisture retention capacity of 3.5 times its weight, beneficial aspects for plant growth.

1. Introduction

There are concerns for the realization of organic improvers, which must be added to the soil in situ to maintain/improve its physical, chemical and/or biological properties; organic fertilizers derived from organic raw materials of animal/vegetable origin, composed of organic components to which the main fertilization elements are chemically bound in organic form or are part of the material; organo-mineral fertilizers obtained by chemical reactions or by dry mixing of one or more organic fertilizers and/or one or more organic matrices with one or more inorganic fertilizers; and last but not least, finding organic or inorganic matrices for the immobilization of bacteria beneficial to the soil and cultivated plants [1,2,3,4]. The good management of organic wastes such as wool from livestock farms or private sheep breeders requires the superior exploitation of their potential as organic raw material by using them to produce compounds with superior added value, including organic or organo-mineral fertilizers/fertilizers [2,5,6,7,8]. Both the reduction of the excess use of mineral fertilizers, by replacing them with enriched organic and/or organo-mineral fertilizers, and the valorization of organic waste, in the case of wool waste - major sources of pollution, by making such fertilizers, lead to avoiding major economic and environmental imbalances [2,9,10]. In this context, the project aims to create fertilizers based on wool waste in the context of sustainable agriculture, products with added value in a circular economy, which, in addition to macroelements and microelements, contain, as basic components, organic compounds and biostimulants obtained from the recovery and efficient reuse of nutrients from organic waste [2,11,12,13,14,15].

2. Materials and methods

Only metrologically verified, regulated or calibrated measuring devices and devices were used for the experiments. The assurance of the metrological verification is done by the person in charge of the test and consists in examining the period of validity inscribed on the verification labels applied to the devices.

Table 1

Equipment, materials and reagents used

Crt. no	Equipment, materials and reagents used
1	Keratin hydrolyzate from raw sheep's wool
2	Keratin hydrolyzate from pelleted sheep's wool (type A pellets)
3	Keratin hydrolyzate from pelleted sheep's wool (type B pellets)
4	NaOH
5	$Ca(OH)_2$
6	Distilled water
7	HCl (5%)
8	Micropipettes and tips
9	Laboratory glassware
10	Centrifuge tubes
11	Incubator for the cultivation of microorganisms
12	Incubator with shaking and temperature control
13	Water bath with stirring and temperature control
14	pH-meter
15	Spectrophotometer
16	Centrifuge
17	Oven - stove
18	Freezer
19	Oven - oven Cultures of microorganisms from the CMIT collection of USVT
20	Components for the preparation of culture media for microorganisms

Hydrolysis was performed to obtain working material for subsequent stages of microorganism growth testing. At the same time, according to the method in this case, 23 types of tri-factorial tests (3 factors studied at two levels) of decomposition of sheep wool and pelletized wool were performed. Regarding the investigated factors, the following technological conditions of wool decomposition were applied:

1. **factor A -** time of the first stage of hydrolysis - 12 hours, (upper limit 24 hours).
2. **factor B -** time of the second hydrolysis stage - 12 hours, (upper limit 24 hours).
3. **factor C -** the amount of added enzyme (in relation to the mass of dry wool): 24 hours.

Alkaline hydrolysates were tested by the diffusimetric method to establish the inhibitor/nutrient quality of the products obtained by the chemical (alkaline) hydrolysis technique, the same diffusimetric method will be applied as a rapid test to determine if the enzymatic hydrolysates obtained from wool and pellets inhibit/ promotes the growth of telluric microorganisms beneficial to plants. For the cultivation of microorganisms in Petri dishes and

the application of disks impregnated with the previously obtained hydrolyzates, two formulas of culture media were used, the simple agar medium and YMA medium
The raw sheep wool was first washed several times in warm water until a clean, impurity-free material was obtained. After the last wash, it was mechanically wrung out and dried in an oven at 60^0C. In the case of wool pellets marked A and B, they have not been washed. Although it is possible that they contain impurities, washing them would have led to the modification of the physico-chemical properties of the thermally pretreated (pelletized) wool and to losses due to mixing with water. After drying, both wool and pellets were stored in a desiccator.

3. Results

The different compositions made for testing bacterial growth were dispensed into sterile Erlenmayer flasks of 100 ml total capacity, covered with a cotton plug for aeration, containing 20 ml of liquid medium. The 10 experimental variants are described below, which were each inoculated with 600 µl of fresh inoculum of B.l.1969 / 20 ml of liquid medium.

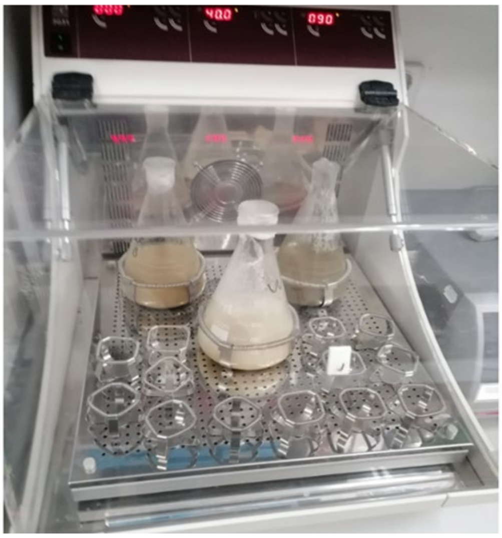

Figure 1. Hydrolysates of raw wool and pelleted wool in the shaking incubator

To test the quality of nutrients for the cultivation of bacteria of keratin hydrolysates, an experimental model was made divided into 10 experimental batches:

1. From 1 to 3 – batches obtained from liquid hydrolysates

The 3 types of liquid hydrolyzates (wool, pellet A, pellet B) were kept in the freezer. After thawing, 20 ml of liquid enzyme hydrolysates of each type were dispensed into sterile 100 ml Erlenmayer flasks. To these was added 0.1g of NaCl to simulate the same osmotic balance as that of the original medium used for the cultivation of bacteria of the genus Bacillus, namely LB.

2. From 4 to 6 – batches obtained from combinations of liquid hydrolysates and dry hydrolysates

These batches were obtained by combining the 3 types of liquid hydrolysates with dry enzymatic hydrolysates (wool, pellet A, pellet B). Each vial containing the same total volume of 20 ml was obtained from 10 ml of liquid hydrolyzate + 10 ml of distilled water to which 0.21 g of the same enzymatic hydrolyzate was added, but dried at 105^oC. The same amount of salt, namely 0.1g NaCl, was added. These batches aim to highlight the loss/maintenance of the nutritional qualities of the hydrolysates subjected to drying at 105^oC.

3. **From 7 to 9 – batches obtained from rehydrated dry hydrolyzates**

These batches were obtained from the 3 types of dry enzymatic hydrolysates (wool, pellet A, pellet B) rehydrated. Each vial containing the same total volume of 20 ml was obtained from 20 ml of distilled water to which was added 0.21 g of enzymatic hydrolyzate dried at 105°C. The same amount of salt, namely 0.1g NaCl, was added. These batches aim to highlight the nutritional qualities of the hydrolysates dried at 105°C, without benefiting from the nutrient intake from the variants preserved by freezing.

4. Batch 10 – control batch

As a control batch, the liquid LB medium was prepared, a common medium used to cultivate bacteria, including those of the Bacillus genus. LB medium contains: 0.2 g tryptone, 0.1 g yeast extract, 0.1 g NaCl, dissolved in 20 ml distilled water.

The vials thus prepared, covered with cotton plugs and gauze, were sterilized by autoclaving at 121°C. Until inoculation, they were kept in the refrigerator. The inoculation was done with 600 µl of the fresh inoculum of B.l.1969.

After inoculation, they were incubated at 37°C for a period of 24 hours. During the cultivation period, 14 samples were taken, at certain time intervals as described in table 2.

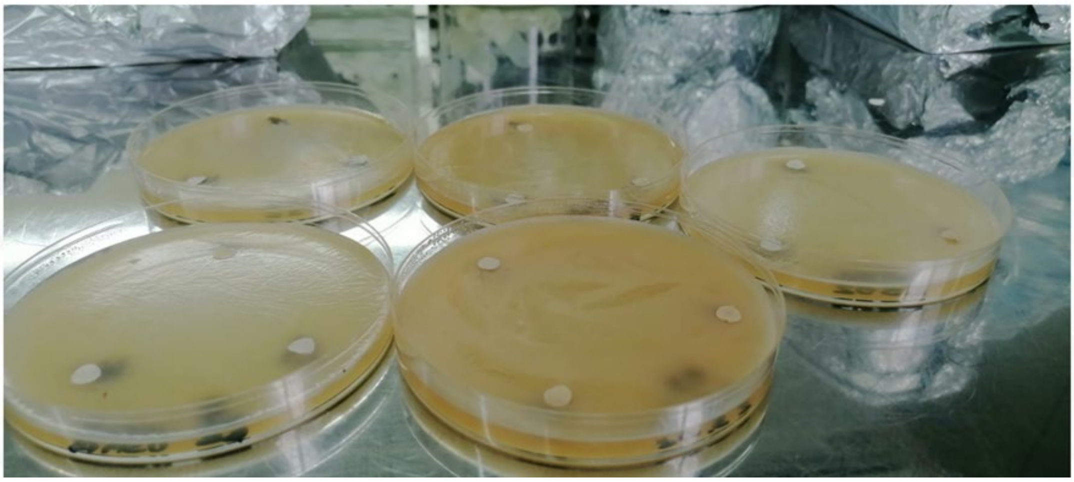

Figure 2. Plates of Bacillus bacteria grown on plain agar with discs impregnated with keratin hydrolysates

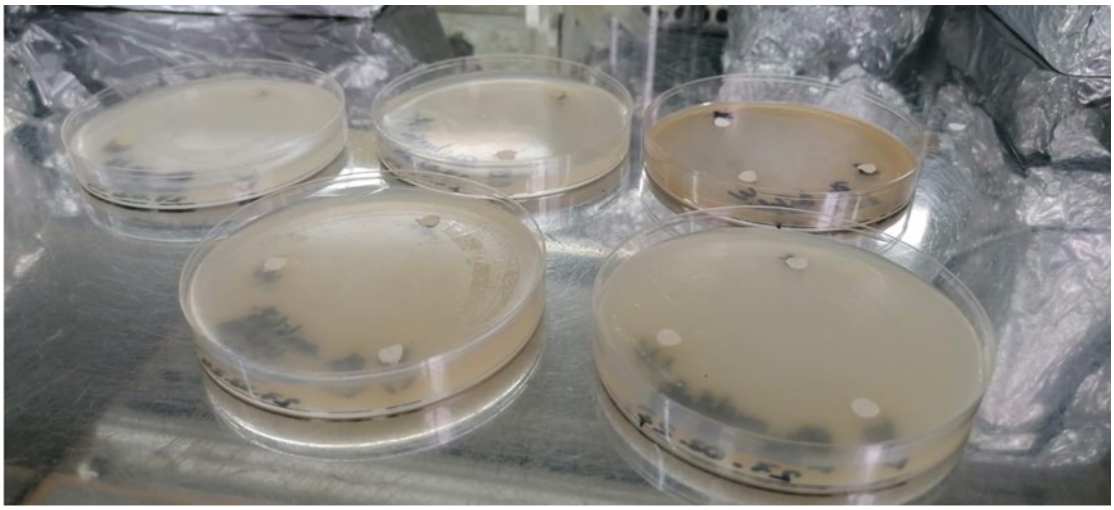

Figure 3. Plates with bacteria of the genus Rhizobium grown on YMA medium, with discs impregnated with keratin hydrolysates

Table 2

Sampling of B.l.1969 cultures on keratin hydrolysates

Sample no.	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14
Time of sampling	0*	0**	1	2	3	4	6	8	10	12	14	16	18	20	24

0- sample taken before inoculation*
*0**- sample taken after inoculation*

4. Discussion

These results are an important milestone in this field as they clearly demonstrate that the starting idea of the research is feasible; more precisely, the growth of some bacteria with an important role in the soil is possible on media enriched with wool digestate.

5. Conclusions

Applying the enzymatic hydrolysis method, keratin hydrolyzates can be obtained from sheep wool and from sheep wool pre-treated thermally by pelletizing. Keratin hydrolysates obtained by applying the methodology described in this research contract do not inhibit the growth of the tested microorganisms. Keratin hydrolysates obtained by applying the methodology described in this research contract can be used for the development of tested microorganisms, especially bacteria from the genera Bacillus and Rhizobium, which can be applied in agricultural crops to maintain plant health, improve agricultural production and restore soil biodiversity. Keratin hydrolysates obtained by applying the methodology described in this research contract retain their nutritional qualities by preservation at low temperatures (by freezing) and lose their nutritional qualities if they are conditioned by dehydration at the temperature of water evaporation.

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Conflicts of interest: The authors declare no conflict of interest

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Review

A COMPARATIVE EVALUATION OF ORGANIC AND CHEMICAL FERTILIZATION EFFECTS ON SHRUB FRUIT PRODUCTIVITY

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Keywords: *aquaponic installations, recirculation systems, wastewater treatment, water filtering,*

Abstract: Soil is an essential but finite resource for plant growth and performance. It deteriorates rapidly in intensively used agricultural areas, but its evolution and recovery are extremely slow. As a result, the deficit of nutrients and organic matter in agricultural systems is at a critical level. Excessive application of mineral fertilizers to provide plants with macronutrients (N, P, K) and micronutrients (Fe, Cu, Mn, Zn,) can be problematic, given that these products may include harmful substances, are often expensive and can have a negative impact on the environment. The amount of organic waste generated in urban and industrial environments is also constantly increasing worldwide, which has led to the development of ecological solutions to manage this waste, such as composting. Thus, the need to balance economic and environmental aspects has led to an increased use of recycled waste, which is transformed into organic fertilizers, capable of satisfying plant needs by releasing nutrients, while contributing to improving soil quality. This paper presents a parallel between the application of organic substances as a feasible option instead of chemical fertilizers, in fruit shrub crops by examining their impact on soil fertility, plant nutritional health, and production yield.

1. Introduction

In recent decades, due to the continuous development of the world population and the increasing demand for food, intensive agriculture has been adopted. Thus, the excessive use of chemicals for soil fertilization and increased production has adversely affected the maintenance of soil health and crop yield [1]. In this sense, contemporary horticulture must be re-evaluated, and diversify its methods, by including opportunities and technological innovations from various fields. These could include, for example, the biotechnology-based industry, in an approach focused on the circular economy [2]. One of the challenges of sustainable agriculture is to reduce the large amounts of fertilizers used without negatively affecting the nutritional needs of plants and without compromising crop production and the quality of plant products. In particular, the excessive use of chemical fertilizers has caused soil degradation (e.g., increased salinity or acidification), pollution of surface and groundwater, and an increase in greenhouse gas emissions [3]. In addition to the effects of inorganic substances on the chemical composition of the soil and certain environmental aspects related to climate change, the decrease in the activity of microorganisms must also be analysed [4]. As in other branches of agriculture, an ecological approach is needed in fruit tree crops, by introducing organic substances to support the maintenance of soil health, implicitly the development of crops and the quality of fruits. Among the best-known fruit trees, there are blackberries, blueberries, raspberries. These fruits are increasingly appreciated by consumers, due to their beneficial effects on human health, supported by numerous scientific evidence.

Consumer awareness of the importance of protecting the environment, but also of food quality, has determined an upward trend in organic production. Due to this trend, most research has focused on the effects of organic production [5]. The use of fertilizers at key moments in the development of plant products is essential for increasing production. Other important aspects are related to the ideal amount and method of application (directly in the soil, foliar, by spraying), thus influencing the rate of absorption of fertilizers by plants. [1,6]. Chemical fertilizers are used for their ability to act quickly and influence soil properties, fruit quality, but also their nutrient composition [7]. Although they have a number of benefits in agriculture, without controlled management, excessive application of chemical fertilizers can have numerous negative effects. In addition to reducing sustainable crop productivity, the reduction of friendly predators can increase the risk of residual accumulation in the soil and groundwater contamination [8, 9].

For example, studies have shown that simply increasing the application of nitrogen-based fertilizer (which is the most important nutrient) not only does not generate significant economic benefits, but also causes imbalances in plant nutrition [10]. In order to maintain soil fertility and crop development, while protecting the environment, attention has been directed towards addressing organic alternatives. Numerous studies present the benefits of applying organic fertilizers, suggesting a consistent reduction in soil-borne diseases, increased plant defence mechanisms, and an increase in both the diversity of microorganisms and biological activity in the soil [11]. Common organic sources of nitrogen range from agricultural waste to manure, which is a relatively cheap and abundant source of nitrogen [12]. Among the significant benefits of organic fertilizers are the growth of beneficial microorganisms in the soil and the improvement of its physical characteristics and fertility, but the major disadvantage remains the inability to quickly respond to the nutritional needs of plants for nitrogen, due to the slow rate of nitrogen mineralization [13].

2. Chemical Fertilizers

The continuous increase in the consumption of nutrient-rich fruits has led to the intensification of crops to meet market demands.

Blueberries, rich in antioxidants, are appreciated by consumers due to their beneficial effects on human health. It has been shown that fertilization is necessary in blueberry cultivation to ensure adequate productivity [14]. Scientific research supports that chemical fertilizers obtain the highest values on the nutritional (high content of N, P, K) and productive parameters of blueberries [15]. The main effects and interactions between fertilizers used in the soil (nitrogen, phosphorus and potassium) and the optimal level of fertilizer application for the vegetative and crop stages, leaf nutrients and berry yield of wild blueberry (Vaccinium angustifolium Ait.) were investigated. The results of the study emphasize the importance of applying balanced fertilization, with the optimal fertilizer doses being presented in Table 1.

Table 1

Appropriate fertilizer application rates for the vegetative and crop stages of wild blueberry [6].

	Application period		
Fertilizer applied	**Pre-emergence of shoots in the growing year Kg/ha^{-1}**	**The leaves of the vegetative year %**	**The leaves of the crop year %**
N	30	1,8-2,03%	1,5-1,7%

P	45	0,155-0,160%	0,158-0,164%
K	30	0,53-0,55%	0,535-0,545%
Ca	-	0,44-0,46%	0,465-0,495%
Mg	-	0,115-0,13%	0,115-0,125%
B	-	24-26 ppm	18-22 ppm

Another study suggests that foliar applications of Ca and B did not lead to significant increases in fruit quality, yield estimates, or fruit firmness (such as berry firmness and weight) during treatments in northern blueberry (Vaccinium corymbosum L.) [16]. In Canada, the long-term effects of annual nitrogen (N) applications at different rates by broadcast (BROAD) and fertigation (FERT) techniques on soil properties and blueberry yield were evaluated. From the results presented, it can be concluded that fertilizing mature plants with ammonium sulfate above the suggested rate is not a sustainable choice for blueberry cultivation, by decreasing production and increasing soil electrical conductivity (EC) beyond acceptable limits, Table 2.

Table 2

Total berry yield (kg ha−1) with annual N applications by fertigation (FERT50, 50%; FERT-100, 100%; FERT-150, 150%; FERT-200, 200%) and broadcast (BROAD50, 50%; BROAD-100, 100%; BROAD-150, 150%; BROAD-200, 200%) methods for blueberries (Vaccinium corymbosum) during two production periods (2010–2012 and 2013–2015) [8].

First period	2010	2011	2012	Second period	2013	2014	2015
CONT[a]	2375	6351	9563	CONT	14696	21826	20613
FERT-50	2765	7722	13786	FERT-100	20746	24672	32444
FERT-100	2825	8340	13380	FERT-150	20397	23369	27211
FERT-150	3146	9431	14908	FERT-200	20019	23492	22873
BROAD-50	2552	6779	11694	BROAD-100	19461	23501	30503
BROAD-100	2442	7194	11629	BROAD-150	20615	24860	29620
BROAD-150	2598	8029	14040	BROAD-200	21345	25441	29908
SEM[b]	*453*	*1309*	*1331*		*1459*	*1721*	*1557*
P values	*0.667*[c]	*0.305*	*0.005*		*0.001*	*0.447*	*< 0.001*

[a] CONT: control (0 kg N ha^{-1}).
[b] SEM: standard error of the mean.
[c] Probability values

The aim of a study was to determine the main effects and interactions of N-P-K fertilizers applied to the soil on the development, growth and production of wild berries. The results obtained recommended the use of 35 kg ha -1 N, 40 kg ha -1 P and 30 kg ha -1 K at the beginning of shoot germination each year for low bush blueberries in Scotland. The proposed rates improved the number of flower buds, berries per stem and berry productivity, without causing excessive stem growth (stem lengths over 20 cm are considered excessive and lead to low harvest efficiency) [17]. Inorganic nitrogen fertilizers are commonly found in commercial blueberry plantations. However, this form of nitrogen can stimulate excessive growth of various weed species, which can ultimately reduce the benefits obtained from fertilization. Therefore, a low crop density is recommended to maximize fruit production and below 25 plants m-2 to optimize the efficiency of inorganic N fertilization [18].

Understanding the annual accumulation of nutrients and the rapid absorption phases facilitates a more efficient management of fertilization programs. Thus, red raspberry (Rubus idaeus) and blackberry (Rubus ssp. rubus) plantations were analysed to find out the required nutrient supply and the efficiency of fertilizer absorption. In addition to N, the other nutrient largely removed during fruit harvesting and pruning is K (Tables 3 and 4).

(Table 3)

Removal of nutrients in summer-bearing 'Meeker' red raspberry and 'Black Diamond' and 'Marion' trailingblackberry from pruning of senescent floricanes in August or September (raspberry) or mid-August (blackberry), and for leafsenescence on primocanes in autumn (raspberry only)[19].

	Macronutrients (lb/acre)^z						Micronutrients (oz/acre)^z				
Crop and activity	N	P	K	Ca	Mg	S	B	Cu	Mn	Zn	Fe
Summer-bearing raspberry Floricane pruning											
August	17.3	1.2	9.4	15.3	3.1	0.9	1.7	0.2	2.1	0.5	—
September	11.8	0.9	6.5	12.7	2.4	0.8	1.0	0.2	2.1	0.4	—
Leaf senescence	9.5	0.7	4.2	5.0	2.1	0.4	0.8	0.1	1.2	0.1	—
Trailing blackberry Floricane pruning											
'Black Diamond'	27.4	4.2	35.8	25.4	4.2	1.8	0.1	0.02	1.1	0.2	0.7
'Marion'	35.7	4.8	36.8	35.1	7.7	2.4	0.3	0.02	1.3	0.2	0.9

^{z}1lb/acre=1.1209kg·ha^{-1}, 1 oz/acre = 7 0.0532 g·ha^{-1}, N = nitrogen, P = phosphorus, K = potassium, Ca = calcium, Mg = magnesium, S = sulfur,B = boron, Cu = copper, Mn =manganese, Zn = zinc, Fe = iron.

Table 4

Removal of nutrients per ton (fresh weight) of harvested fruit in summer-bearing 'Meeker' red raspberry and 'BlackDiamond' and 'Marion' trailing blackberry [19].

	Macronutrients (lb/ton)^z						Micronutrients (oz/ton)^z					
Crop	N	P	K	Ca	Mg	S	B	Cu	Mn	Zn	Fe	Al
Summer-bearing raspberry	3.49	0.47	3.04	0.32	0.37	0.17	0.15	0.03	0.11	0.07	—	—
Trailing blackberry												
'Black Diamond'	2.89	0.53	3.01	0.45	0.27	0.20	0.05	0.02	0.19	0.06	0.15	0.40
'Marion'	2.87	0.63	3.02	0.73	0.37	0.19	0.05	0.03	0.23	0.08	0.19	0.43

^{z}1 lb/ton = 0.5000 kg·Mg^{-1}, 1 oz/ton = 31.2500 g·Mg^{-1}, N = nitrogen, P = phosphorus, K = potassium, Ca = calcium, Mg = magnesium, S = sulfur, B = boron, Cu = copper,Mn = manganese, Zn = zinc, Fe = iron, Al = aluminum.

Fertilization at different rates of N can affect the concentration of other nutrients not only in the leaves but also in other parts of the plant. Monitoring plant development and nutrient levels is suggested to adjust fertilization plans [19]. The response of 'Meeker' red raspberries grown in Washington, USA, to different rates of N fertilizer was evaluated to inform future nutrient management guidelines. Urea treatments (46% nitrogen (N)) were applied to the surface of raised beds of 'Meeker' raspberry plots established at controls, low, medium and high rates (0, 34, 67 and 101 kg N ha −1 , respectively) in 2019 and 2020, Table 5.

Table 5

Berry weight, average plant yield and total yield of Florican red raspberry 'Meeker' fertilized with different rates of nitrogen (N) fertilizer, 2020 [20].

Treatment	Berry Weight (g)	Average Plant Yield (kg Plant^{-1})	Total Yield (kg Plant^{-1})
N fertilizer rate (A)			
Control (0 kg N ha^{-1})	3.02 ^{z}	0.311	0.933
Low (34 kg N ha^{-1})	3.03	0.385	1.15
Medium (67 kg N ha^{-1})	3.10	0.325	0.977
High (101 kg N ha^{-1})	3.10	0.349	1.05
Harvest time (B)			
Early	3.35 a	0.212 c	- ^{y}
Middle	3.08 b	0.542 a	-
Late	2.75 c	0.274 b	-
Significance ^{x}			
N fertilizer rate (A)	0.78	0.85	0.85
Harvest time (B)	<0.0001	<0.0001	-
Interaction A × B	0.55	0.85	-

z Data are shown as means; means followed by a different letter within a group are significantly different at p ≤ 0.05 using a comparison of means with a Tukey's honestly significant difference test. y (-) Not applicable as total yield was calculated over the entire harvest season. x Significance was determined at p < 0.05.

The lack of a N fertilizer response for most of the measured variables led to the rejection of the experimental hypothesis that plants receiving higher N fertilizer rates exhibit improved performance [20]. Following a comprehensive evaluation of principal component analysis and multifactorial analysis of variance, the best fertilization combination for high-yielding and good-quality blueberries was found to be N1P2K2 (F2). That is, the best fertilization effect was that including N 100 g/plant, P2O5 25 g/plant, K2O 50 g/plant applied as ammonium sulfate (472 g/plant). g/plant), superphosphate (41 g/plant), and potassium sulfate (79 g/plant), respectively [21].

3. Common organic sources of nitrogen

The main sources of nitrogen for organic farming are compost, green manures, natural fertilizers and residues from biological processes, so the total release of nitrogen in plant-available forms is related to the mineralization capacity of the soil together with nutrient factors (energy, C and N content, among others) and soil factors (temperature, moisture, oxygen, acidity), as reported by several authors [22]. Common organic sources of nitrogen range from cover crops to manure (or manure-derived products) and fish by-products, vegetable hydrolysate (e.g. corn liquor), molasses, vegetable and animal by-products (e.g. vegetable-based meals such as soybean meal and animal-based meals such as feathers, bones). Although manure is an abundant and inexpensive source of nitrogen, USDA organic regulations permit the use of manure only with a pre-harvest restriction (90 days for blackberries) [12, 23].

Fertilization of blueberries has been the subject of much research. Blueberries prefer acidic, well-drained, moist, humus-rich soils that are lower in nutrients than other fruit species [24]. The literature shows that adding composted yard waste to mulch increased soil and leaf potassium (K) but had little effect on plant nitrogen (N). However, when this compost was used as a pre-plant amendment, soil pH increased to levels above the recommended range for blueberries [25]. It has been hypothesized that composted wood chips (CRW) is an effective alternative organic fertilizer for blueberry plants when weeds are present, as ericaceous shrub species are generally more efficient in using organic nitrogen than herbaceous weed species [18]. A long-term (10-year) study presents the influence of the choice of organic production system on yield and costs and economic profitability of highbush blueberry (Vaccinium corymbosum L.). Thus, treatments included planting method (flat or raised beds), fertilizer source (granular feather meal or fish solubles) and rate ('low' and 'high' rates of 29 and 57 kg ha -1 N during establishment, gradually increased as the planting matured to 73 and 140 kg ha -1 N, respectively), mulch (sawdust, composted yard waste covered with sawdust (compost + sawdust), or black woven polyethylene ground cover (weed mat)], and cultivar ('Duke' and 'Liberty'), Table 6.

Table 6

Results of analysis of variance for the impact of year (2008–16; n = 9 for yield; n = 7 for fruit quality variables), planting method (raised bed or flat ground; n = 2), fertilizer source and rate (feather meal or fish solubles at low or high rate of nitrogen; n = 4), mulch (sawdust, yard debris compost topped with sawdust, weed mat; n = 3) and cultivar (Duke, Liberty; n = 2). Actual P value provided unless nonsignificant [26].

Treatment	Yield (kg/plant)	Berry wt^z (g)	Berry diam (mm)	TSS^y (%)	Firmness (g·mm^{-1} deflection)
Year (yr)	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001
Planting Method (PM)	<0.0001	<0.0001	0.001	<0.0001	NS
Yr · PM	<0.0001	0.0027	NS^x	NS	NS
Fertilizer (Fert)	<0.0001	0.0031	0.002	<0.0001	<0.0001
Yr · Fert	<0.0001	0.0113	0.0001	NS	<0.0001
PM · Fert	NS	NS	NS	0.0477	NS
Yr · PM · Fert	NS	NS	NS	0.0131	0.0404
Mulch	<0.0001	0.0095	NS	NS	0.0088
Yr · Mulch	0.0042	NS	NS	<0.0001	<0.0001

PM · Mulch	0.001	NS	NS	NS	NS
Yr · PM · Mulch	0.0116	NS	NS	NS	NS
Fert · Mulch	<0.0001	NS	NS	NS	NS
Yr · Fert · Mulch	0.0014	NS	NS	NS	0.0455
PM · Fert · Mulch	NS	NS	NS	NS	NS
Yr · PM · Fert · Mulch	NS	NS	NS	0.0308	NS
Cultivar (cv.)	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001
Yr · cv.	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001
PM · cv.	<0.0001	NS	NS	<0.0001	NS
Yr · PM · cv.	0.012	NS	0.0027	NS	NS
Fert · cv.	<0.0001	0.0002	0.0002	<0.0001	<0.0001
Yr · Fert · cv.	<0.0001	0.0173	NS	0.0011	0.0006
PM · Fert · cv.	0.0002	NS	NS	0.0379	NS
Yr · PM · Fert · cv.	NS	NS	NS	NS	NS
Mulch · cv.	<0.0001	NS	0.0005	NS	NS
Yr · Mulch · cv.	0.0017	0.0085	NS	0.0324	NS
PM · Mulch · cv.	0.0005	NS	NS	NS	NS
Yr · PM · Mulch · cv.	0.0386	NS	NS	NS	NS
Fert · Mulch · cv.	<0.0001	NS	NS	NS	NS
Yr · Fert · Mulch · cv.	NS	NS	NS	NS	NS
PM · Fert · Mulch · cv.	NS	NS	0.043	NS	NS
Yr · PM · Fert · Mulch · cv.	NS	NS	NS	NS	NS

The research results demonstrate the importance of choosing organic treatments, where fertilization with feather meal and growing with a weed mat led to an additional 20% increase in yield for the blueberry variety "Duke" (to 10.2−19.3 t ha -1), but had a reduced effect on the "Liberty" variety (13.5−22.7 t ha). Equally important is the interaction of treatments to obtain maximum yield of blueberry crops [26]. The results of an experiment conducted at ICDP Pitesti-Maracineni show that organic fertilizers had a positive effect on both the quantity and quality of blueberry fruits. Thus, of the two organic fertilizers used: Codamix (0.25%) and Ecoaminoalga (0.25%), the latter had a greater effect on crop yield, and both fertilizers are recommended for increasing quality. Tables 7 and 8 show the interdependence between the analysed characteristics. Fruit production per plant was negatively, distinctly significantly correlated with fruit firmness (Table 7), the correlation coefficient being r=- 0.208.

Table 7

Pearson correlation coefficients for productivity and main biophysical parameters of fruits (mass, firmness and color) [1].

Pearson Correlation		Yield (g/bush)	Fruit weight (g)	Firmness (Hpe)	L*	a*	b*
Yield (g/bush)		1					
Fruit weight (g)		0.063	1				
Fruit firmness (HPE)		-0.208(**)	0.060	1			
L		-0.184(*)	0.397(**)	0.056	1		
a*		-0.009	0.053	0.023	0.017	1	
b*		0.075	-0.178(*)	0.012	-0.470(**)	0.072	1
	Sig.	0.309	0.010	0.869	0.000	0.297	
	N	213	213	213	213	213	213

** Correlation is significant at the 0.01 level (2-tailed).
* Correlation is significant at the 0.05 level (2-tailed).

The soluble solids content is significantly negatively correlated with the value of the colour coordinate b (Table 6), the correlation coefficient being r=-0.161, which means that bluer fruits (the value of the coordinate b decreases) have more soluble solids.

Table 8

Pearson correlations coefficients for the quality indicators for the studied blueberry varieties [1].

Pearson Correlation		Total sugar content (%)	Total acidity (%)	Total soluble solids (°Brix)	L*	a*	b*
Total sugar content (%)		1					
Total acidity (%)		0.057	1				
Total soluble solids (°Brix)		0.249	0.206	1			
L*		0.231	-0.168	0.114	1		
a*		0.126	-0.195	-0.086	0.017	1	
b*		-0.049	-0.187	-0.161(*)	-0.470(**)	0.072	1
	Sig.	0.839	0.430	0.020	0.000	0.297	
	N	60	60	213	213	213	213

* Correlation is significant at the 0.05 level (2-tailed).
** Correlation is significant at the 0.01 level (2-tailed).

4. Combined application of fertilizers in berry plantations

The aim of the research was to evaluate certain biochemical parameters (organic acids, total polyphenol content, total dry matter content, total sugar, and anthocyanin pigments) in blueberry fruits (*Vaccinium corymbosum* L.). The use of organic and mineral fertilizers at specific stages of plant development proved to be a highly important strategy for improving plant production. Two organic products—Algacifo 3000 (2 L/ha) and ERT 23 Plus (1 L/ha)—and one chemical product—Poly-Feed 19-19-19 + ME (10 kg/ha)—were used as foliar fertilizer treatments. The results indicated that foliar application of the organic treatments significantly enhanced fruit quality. Thus, it can be concluded that the fertilizer composition had a positive effect on the vegetative and biochemical parameters of the fruits; however, the experimental year had a more significant impact [11].

There are numerous reasons for using natural zeolites, particularly clinoptilolite (a natural zeolite), the most important being their positive effect on soil and plants by increasing the soil's electrical conductivity, thereby enhancing nutrient retention capacity and soil pH. Moreover, natural zeolites are an important source of many nutrients (N, K, Ca, Mg, micronutrients). They improve water use efficiency by increasing the soil's water-holding capacity and the availability of water to plants, thus directly and indirectly improving fruit quality [7].

To evaluate the effect of organic fertilizers on blueberry (*Vaccinium corymbosum* L.) cultivation, an experiment was conducted using the cultivars 'Corona', 'Legacy', and 'Liberty'. The fertilizers applied included: compost (CM), Purely Lysine (PL), Purely Grow (PG), Fertil (F), lupin meal (LM), blood meal (BM), along with a control treatment without fertilization (C) and two conventional treatments with urea (CF) and sodium nitrate (S). The results of the experiment indicate that lupin meal achieved the highest values for most evaluated parameters (vegetative growth and leaf nitrogen concentration before senescence, yield, and fruit weight). Thus, it is suggested that future experiments on organic fertilization in blueberries should include combinations of different nitrogen sources and consider fast-, medium-, and slow-release nitrogen supply rates [22]. The addition of yard waste compost to mulch was shown to have the potential to increase potassium (K) levels in soil and leaves, but had limited effects on plant nitrogen (N) content [25].

5. Discussion

Chemical fertilizers are used due to their ability to produce rapid effects and to modify soil characteristics, fruit quality, and their nutrient composition [7]. Although they have multiple advantages in the agricultural system, the uncontrolled use of chemical fertilizers can have negative consequences. In addition to reducing sustainable crop productivity, the decrease in the number of beneficial predators can lead to an increased risk of soil and groundwater contamination through the accumulation of residues [8, 9]. Another important aspect is related to the inorganic nitrogen-based fertilizers found in berry plantations. They can stimulate the excessive development of various weed species, which can ultimately reduce the benefits obtained through fertilization [18]. Among the notable advantages of organic fertilizers is the stimulation of beneficial microorganisms in the soil, as well as the optimization of its physical properties and fertility capacity [13]. The application of organic fertilizers has the potential to reduce soil-borne diseases, enhance plant defense mechanisms, and increase both the diversity of microorganisms and biological activity in the soil [11].

The main disadvantage is the lack of ability to respond promptly to plant nitrogen nutritional requirements, due to the low rate of transformation of nitrogen into absorbable forms [13]. Some of the organic treatments may also have higher production costs. [27]. A number of studies have highlighted the complexity of nutrient management in perennial cropping systems, as the available nutrient reserves in the soil and plants may provide sufficient nutrients to meet the needs of the vegetation. For this reason, soil organic content and plant resources should be considered as potential sources of nutrients when designing a nitrogen nutrient management plan for crops. Modifying nitrogen fertilizer amounts according to these characteristics could reduce fertilizer costs and the risk of environmental pollution caused by excessive fertilizer use [20].

Synthesis of research on the use of chemical and organic fertilizers and the benefits of their combined action

Chemical fertilizers	Organic fertilizers	Combined application
The best fertilization combination for high-yielding, good-quality blueberries was found to be N1P2K2 [21].	Algacifo 3000 (2L/ha) and ERT 23 Plus (1L/ha) - foliar application to blueberry (Vaccinium corymbosum L.) significantly stimulates fruit quality [11].	Compost from yard waste added to mulch increases potassium in soil and leaves, but reduces nitrogen in plants [25].
A low crop density is recommended to maximize fruit production and below 25 plants m-2 to optimize the efficiency of inorganic N fertilization [18].	Lupin flour (LM) increases blueberry fruit yield [22].	Adult cattle manure, as an organic fertilizer, and pelleted organo-mineral NPK fertilizer ("Excell Orga"-Excell), showed a weak influence on raspberry crop productivity [31].
It is recommended to use 35 kg•ha-^{1} N, 40 kg•ha^{-1} P and 30 kg•ha-^{1} K at the beginning of shoot germination each year for low bush blueberry [17].	Compost of plant origin (VOC, doses of 30 and 40 t ha $^{-1}$) can be used as fertilizer in the sustainable growth of red currants [28].	Intercropping with grass species may be an effective and sustainable alternative to counteract Fe deficiency in blueberries [32].
Specialized studies show that a simple increase in the application of nitrogen-based fertilizer (which is the most important nutrient) not only does not generate significant economic advantages, but also causes imbalances in plant nutrition [10].	Ensuring ample pollination can reduce the amount of nitrogen fertilizer required by 39 kg/hectare in raspberry (Rubus idaeus L.) cultivation [29].	Blueberry bushes foliarly fertilized with fertilizers containing calcium and microelements produced fruits with better quality parameters than unfertilized ones [33].
Foliar applications of Ca and B did not lead to significant increases in fruit type, yield estimate, or quality in northern blueberry cultivation [16].	Poultry litter offers advantages in blackberry production for mitigating the decrease in soil pH that occurs with fertilization [30].	
Increasing the fertilization rate twofold (60kg N/hectare) significantly increased the soil N content to a level higher than the optimal level recommended for blueberry production [27].	Fish-based fertilizer contributed relatively large amounts of sodium to the soil, without any adverse effects being observed [30].	
	Biostimulation (with preparations containing phytohormone precursors and biostimulants) has a beneficial, but not always considerable, effect on blueberry fruit yield [34].	

6. Conclusions

Soil nutrient depletion is a major problem related to soil health. Chemical fertilizers are used for their ability to generate quick results and change soil properties, crop yield and nutrient composition. However, poor management of chemical use negatively impacts agricultural crops and the entire ecosystem by degrading soil, contaminating surface and groundwater sources, and increasing greenhouse gas emissions. In order to preserve soil fertility and promote plant growth while protecting the environment, attention has been focused on addressing organic alternatives.

Similar to chemical fertilizers, organic fertilizers have both advantages and disadvantages. Significant benefits of organic fertilizers include stimulating beneficial microorganisms in the soil, along with improving its physical characteristics and fertility potential. The major disadvantage is the lack of a rapid response to the nitrogen nutrient needs of plants, due to the low efficiency in converting nitrogen into absorbable forms. Some organic treatments may also involve high production costs. In the investigations carried out, the authors summarized the advantages of the interaction between fertilizers, so future studies on the fertilization of fruit shrubs should integrate mixes of various nitrogen sources and analyze fast, moderate and slow nitrogen supplies.

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Review

OBTAINING BIOCHAR FROM ORCHARD AND FRUIT SHRUB RESIDUES

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Abstract: In the context of climate change, sustainable agriculture and the circular economy, a viable alternative to fossil fuels is biomass products. Orchards are among the new sources of biomass purchased for energy use. A significant amount of biological waste is produced each year through the regular pruning and grooming of fruit trees and shrubs. This lignocellulosic biomass, which occurs mainly in the form of leaves, rootstocks, branches and trunks, is a potential high-quality fuel, but is often treated as waste. One of the basic products made from biomass is biochar. Charcoal, known as biochar (BCH), is produced by controlled pyrolysis of woody biomass in an anaerobic environment. In recent years, multiple studies have been carried out on the recovery of residues from both agriculture and orchards. This paper highlights a brief synthesis on the recovery of residues from orchards in the form of biochar.

1. Introduction

Worldwide, more than two billion tons of municipal solid waste are produced annually and this amount is expected to increase by about 70% by 2050. This significant increase in the amount of waste has increased pressure on the environment, negatively affecting soil, air and water resources.

Global municipal solid waste generation in 2020 and projections for 2030–2050 are shown in Figure 1.

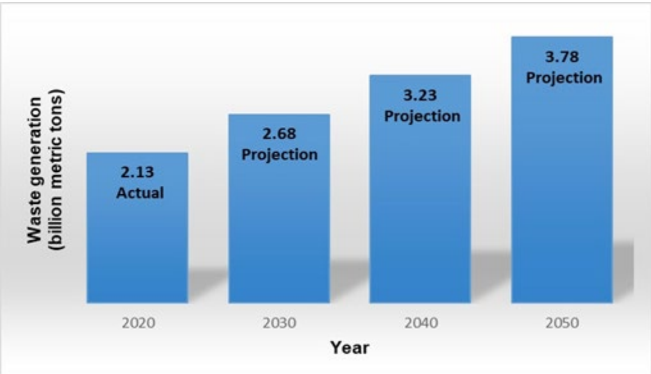

Fig.1. Solid waste generation worldwide (2020–2050, 2024) [1]

Agriculture is among the main global sources of large amounts of solid waste. A study by the Food and Agriculture Organization says agriculture produces more than 140 billion metric tons of biomass each year, and more than two tons are produced daily in rural areas. In addition, the agricultural sector is the second largest emitter of greenhouse gases (19.9%) into the atmosphere, after the energy sector (68.1%) [2].

The burning of waste and the landfilling of agricultural waste endangers food and energy security, as well as human and environmental health [3]. Improper disposal of this waste can lead to significant waste of resources, environmental deterioration, and significant pressure on agricultural environmental protection [4].

Almost 3.7 million hectares of land were planted with fruit in the EU in 2022, accounting for around 2% of the total agricultural land used. Walnut orchards accounted for around 40 % of the total fruit area (see Figure 2), stone orchards around 16 %, stone fruit orchards (apple and pear) a further 16 % and citrus orchards 14 %. The remaining area under fruit was divided between tropical and subtropical fruit (around 5 % of the total fruit area), berries (around 4 %) and other fruit such as table grapes (Fig. 2) [5].

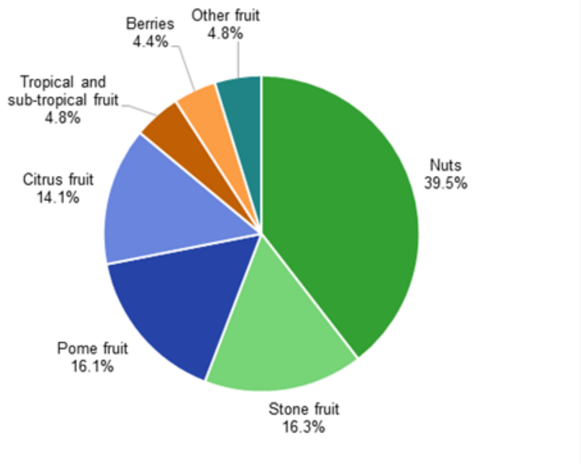

Figure 2: Share of fruit area in the EU (%, fruit type, 2022) [5]

Pruning is necessary for all orchards and takes place at intervals of 1 to 3 years. Approximately 1 to 5 tons of residues are produced as a result of this operation. Traditionally, open burning is used to remove cutting residues, which release a variety of pollutants [6] and is one of the main sources of lead deposition and CO2 emissions in orchard management [7]. Agricultural burning pollutes the air less than car traffic, but produces emissions that are particularly dangerous to human health due to their high particulate matter content.

Biochar is a solid residue produced by the pyrolysis of biomass. It is considered a useful material for use in environmental contexts. An effective adsorbent due to its high porosity [8]. Due to its adsorption characteristics, biochar is a popular candidate for various environmental applications, such as removing pollutants [9], helps store carbon, retain water in the soil, supply nutrients, improve the fertility of the soil on which it is placed, and increase crop productivity [10,11,12,13]. Biochar has been found to be cheaper than activated carbon. Customizable brewing process, dynamic functional groups, condensed carbonaceous matter, and constant chemical characteristics are some of its outstanding features [14,15,16,17,18].

Biochar can be obtained from many different raw materials, such as plant-based raw materials, vegetable and fruit waste raw materials, algae, poultry litter, forest waste, activated sewage sludge, etc. [19, 20, 21, 22, 23, 24, 25].

The production of biochar from residual biomass, including residues from orchards, could be a solution to the growing demand for energy and problems related to biodegradable waste management. This approach to waste management can be vital for environmental protection. The product, which has been produced from woody biomass waste through the pyrolysis process, can be used as a useful renewable fuel in the energy sector. It is possible to be burned in power plants or in cogeneration plants. Biochar can also be used for other interesting energy uses, such as electrocatalysis, fuel cells, supercapacitors, and accumulators [26].

In addition, many studies have shown that fruit waste, especially peels, contain a high amount of phytoconstituents and commercially valuable bioactive compounds, such as essential oils, pigments, antioxidants, and essential oils. These are cheap and abundant resources for use in the pharmaceutical, food and cosmetic industries. In addition, fruit waste, whether raw or modified, can be used as a cheaper biosorbent to remove harmful and hazardous pollutants such as dyes, emerging contaminants, heavy metals, oils, and organic compounds [27].

2. Materials and methods

Biochar is most often produced through the process known as pyrolysis, which is the thermal decomposition of organic substances in the absence of air. Pyrolysis is the process in which biomass is heated in an environment that is partially or completely devoid of oxygen. The lack of oxygen prevents the substance from being completely burned. It is possible that biochar ash, which is rich in nutrients, improves plant nutrition and reduces the amount of fertilizer needed. In addition, biochar improves the ability of soils to retain water., which reduces the amount of water needed for irrigation. In biology, biochar increases bacterial flora, facilitates atmospheric nitrogen fixation, and promotes mycorrhizal association. biochar promotes the growth of microorganisms due to its high porosity [10].

There are several types of thermochemical processes that are used to produce biochar, such as slow pyrolysis, rapid pyrolysis, gasification, and torrefaction. In these processes, the quantity and quality of the biochar produced is very varied depending on the different reaction conditions, especially the amount of oxygen available. For example, high-yielding and high-quality biochar can be obtained for many hours or even days at a pyrolysis temperature of about 400 °C. This temperature is typical for slow biomass pyrolysis [28, 29, 30,31, 32,33, 34].

Regardless of the method or raw material used to obtain biochar, the moisture requirements and size are different for each method, but the process of obtaining biochar includes the following steps: First, the biomass raw material must be dried (the humidity should not exceed 15%). Then, depending on the field of application, the material is shredded to the desired dimensions (the optimum is 8–12 mm). A belt conveyor is used to introduce the resulting biomass into a reactor, where it undergoes the heat treatment process. This process removes moisture and volatile substances from biomass and produces biochar and other by-products such as syngas, tar, wood vinegar, and biogas (fig.3) [35 ,36].

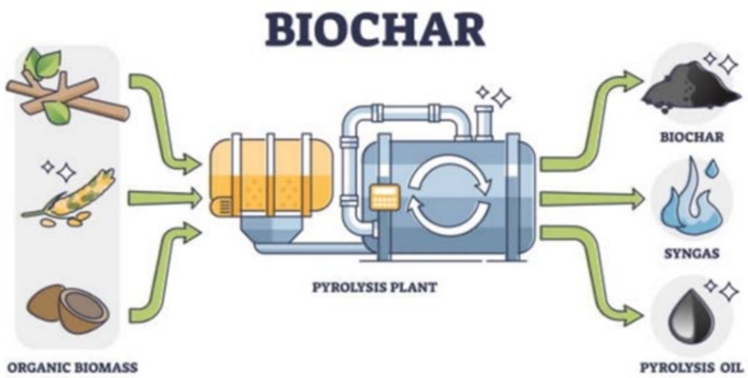

Fig.3. Standard process for obtaining biochar [36]

3. Results

In the literature, the main studies on obtaining biochar and recovering orchard waste had olive trees as raw material [10,37, 38, 39, 40] and vines [41, 42, 43, 44, 45, 46] but residues from cutting apples, pears, plums were also used [18, 47, 48] of tropical fruit trees [49, 50, 51, 52] or even fruit shrubs [53, 54].

A study evaluated the characteristics of biochar obtained from the cutting waste of pear, apple and persimmon fruit trees and how they influence the adsorption of lead (Pb).

First, the raw material was collected, washed with distilled water and dried in the kiln at 110 °C until the weight became constant, then it was cut and sieved until the size of 1-2 mm was reached. A slow pyrolysis reactor at a temperature of 600 °C at a rate of 10 °C min^{-1} was used to obtain the biochar, after which the maximum temperature was maintained for 4 hours before cooling to room temperature.

Biochar from fruit tree residues that was produced by pyrolysis was slightly crushed and sifted to a thickness of less than 0.5 mm. Prior to the adsorption experiment, the biochar samples were washed three times with DI water to remove impurities, such as ash, and soluble salts. Before use, the biochar samples were then dried in an oven at 80 degrees Celsius and sealed in an airtight container.

The results obtained showed that the pH values of the biochar after washing were slightly lower than those of the raw biochar without washing. The washing away of soluble salts from the raw biochar is the main cause of the low pH.

In terms of yield, it was different depending on the raw material and pyrolysis temperature. As for biochar obtained from hair residues, the highest yield was 34.5% obtained at a temperature of 300 °C, and the lowest of 20.3% at 600 °C. Biochar from apple cutting waste had the highest yield of 36.5 % at 300 °C and the lowest of 22.5 % at 600 °C. And in the case of biochar obtained from persimmon tree cutting waste, the biochar yield decreased with the increase in pyrolysis temperature from and 37.9 % at 300 °C to 22.3 % at 600 °C.

And in the case of the elemental composition, a C content was observed, while the H and O content decreased when the pyrolysis temperature increased [55].

Another study presented the feasibility results of pyrolysis of orchard pruning residues to produce biochar. The raw materials were apple (AP), pear (PR) and plum (PL), the most common species of fruit trees (fig.4).

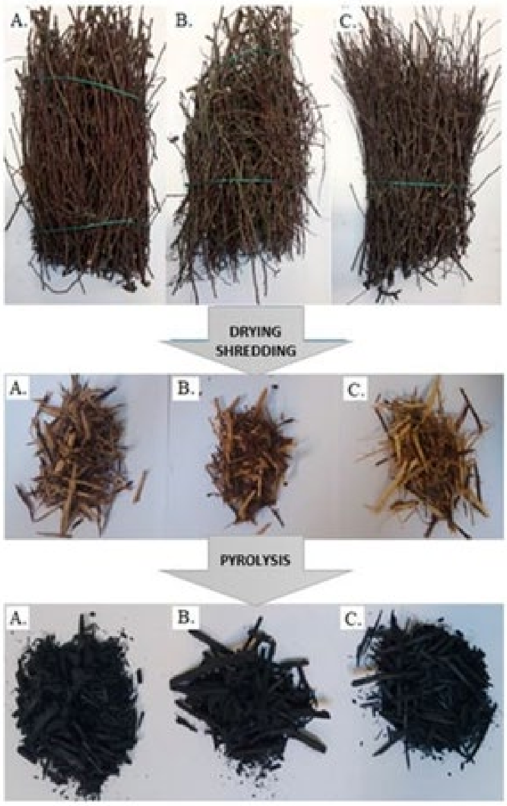

Fig.4. Samples of plum (A), pear (B) and apple (C) cuts, as such, prepared for pyrolysis and after pyrolysis [55]

Two different heating speeds were used, as well as three final pyrolysis temperatures. The heating rates for the slow pyrolysis (SP) and fast pyrolysis (FP) processes were 15 °C/min. From 25 degrees Celsius to 400, 500 and 600 degrees Celsius, the samples were heated. A chemical analysis of the raw materials was carried out and the yields resulting from the pyrolysis process were established.

The yield of biochar produced from cutting residues was between 30-50%. Of the three tree species studied (apple, plum and pear), the type of biomass was secondary to the process conditions used, such as the heating rate and the final pyrolysis temperature. However, the HHV (increased heat output) and carbon content of each raw material used was almost identical, but the ash content was different. For hair, the lowest ash content was obtained; as a result, the ash content of biochar per 1 MJ of energy and the ratio of raw material energy to biochar were also the lowest.

The results showed that we can produce biochar with the highest efficiency with a heating rate of 15 °C/min and a final temperature of 400 °C. In contrast, rapid pyrolysis and high final temperatures (100 °C/min and 600 °C) are required to obtain the biochar with the highest carbon and HHV content. Under these conditions, the biochar obtained had an HHV of over 30 MJ/kg and a carbon content of 80% [56].

Ding and collaborators conducted a study that provides an overview of the use of biochar derived from tropical fruit tree residues and its applications and applications.

They showed that both the production of biochar from tropical fruit tree residues is no different from that of obtaining biochar from other biomass sources (fig.5), but also its uses are quite diverse (fig.6) [49].

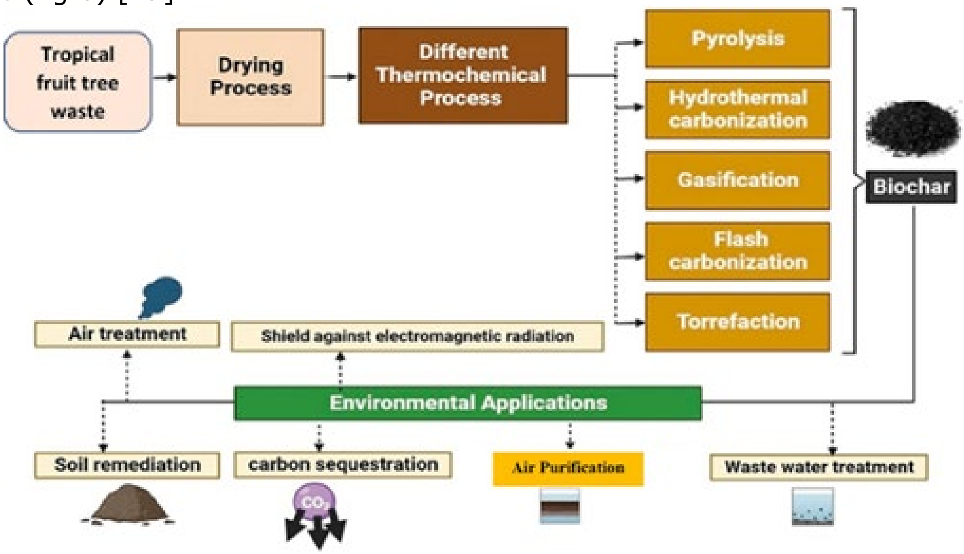

Fig. 5. Techniques for producing biochar from tropical fruit tree waste [49]

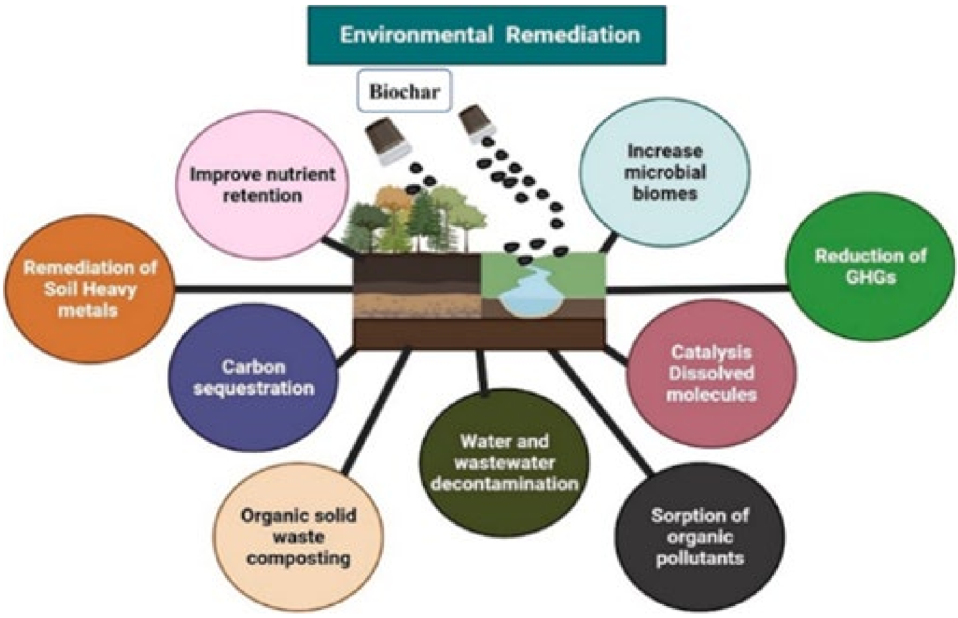

Fig. 6. Application of tropical fruit tree waste biochar for environmental remediation [49]

The residues from pruning the vines were converted into biochar by slow pyrolysis, using CO2 (with a purity of more than 99.9%) as a sweeping gas and oxidizing agent. A fixed-bed reactor (27 cm high, 15.5 cm inner diameter and 3.5 cm wall thickness) kept the chopped vine branches (0.7 cm diameter and 6 cm long) at a temperature of 517 °C (plus or minus 16 °C) for one hour. The cylindrical pieces of biochar were then ground with a soil mill to a diameter not exceeding 2 mm.

The purpose of this potted study was to evaluate the impact of the highly alkaline biochar that is produced from vine pruning residues on the growth performance of bell pepper plants sown in three different soil types in the Muntenia region of Romania. The results showed that in the strongly acidic soil with luvisol, biochar had a positive effect on the cultivated plants, including height, collar diameter, number of leaves and root volume. Changes in the physicochemical properties of the soil, such as electrical conductivity, bulk density, pH, soluble phosphorus, potassium and nitrogen concentrations, contribute to this beneficial effect of biochar.

A promising method for improving soil quality and growing bell pepper plants is the use of a very strong alkaline biochar derived from vine cutting residues as an organic substitute for the in luvisol strongly acidic soil. At the same time, this increases carbon sequestration from the soil while reducing biomass residues and greenhouse gas emissions. Biochar did not affect the growth parameters of bell pepper plants sown in slightly acidic soils of chernozem and slightly alkaline fluvisol. To improve crop growth performance in slightly alkaline or acidic soils, a combination of BC with other organic amendments, lowering the pyrolysis temperature and/or increasing the dose of BC might be good options [57].

Although there is not much data in the literature on obtaining biochar from fruit shrub residues, Kubaczyński and collaborators studied the potential of four types of biochar, namely biochar from potato stems and raspberry stems, biochar from wood scraps and biochar from sunflower peel.

All types of biochar were obtained by pyrolysis at 600 °C, for half an hour, in an N2 atmosphere. Then they were sifted 2 mm and stored in airtight containers in the dark at room temperature.

The results obtained showed that biochar from potato stems and biochar from raspberry stems were able to effectively remove an additional 1% CH4. This was remarkable in terms of their 60% water holding capacity. They have a high potential for CH4, compared to traditional biochar from wood scraps or sunflower husks, and could be a means of managing agricultural waste.

Biochar from raspberry stems and biochar from potato stems are better than wood ones due to their high methane absorption potential and significantly lower carbon dioxide production [54].

4. Conclusions

The production of biochar from residual biomass, including orchard residues, can be a solution to the growing demand for energy, as well as problems related to biodegradable waste management. This product, which is obtained from wood biomass waste through the pyrolysis process, can be used as a valuable renewable fuel in the energy industry, but also in other industries.

The main benefits of using biochar from orchard residues on the environment are: carbon sequestration, reduction of greenhouse gases, soil remediation, soil and wastewater decontamination, absorption of organic pollutants, composting of waste, improves nutrient retention.

Given the fact that not all fruit tree residues have the same composition, i.e. some have a higher carbon content or a higher ash content, preliminary studies are needed in order to be able to choose the most beneficial method for obtaining biochar according to the process parameters (temperature, heating rate, time).

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Review

ROTATING PLANT GROWTH SYSTEMS – A NEW APPROACH TO INDOOR FARMING

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Abstract: Modern agriculture is increasingly constrained by climate change, urbanization, and resource scarcity. In response to these challenges, vertical farming has emerged as a promising alternative, offering space-efficient and climate-resilient crop production solutions. This paper explores rotating hydroponic plant growth systems—a novel approach within controlled environment agriculture (CEA)—designed to optimize spatial efficiency, nutrient delivery, and crop exposure. The paper begins by outlining the detrimental effects of climate change on agricultural productivity, including altered precipitation patterns, increased pest pressures, and reduced yields. In contrast, protected agriculture, especially in the form of automated, closed-loop hydroponic systems, offers significant advantages in terms of resource use efficiency and crop consistency. Among these, rotating systems stand out for their cylindrical design, which ensures uniform light distribution and nutrient access while enabling full automation and modular scalability. A comparative analysis between rotating and conventional vertical systems highlights key differences in water use, energy demand, technological complexity, and productivity. Despite higher upfront costs, rotating systems demonstrate superior yield per unit volume and align well with sustainable development goals. The paper concludes that such systems hold strong potential for urban agriculture and decentralized food production, especially when integrated with renewable energy and digital monitoring technologies. Further research is recommended to evaluate crop-specific performance, economic viability, and life-cycle sustainability. The study contributes to the advancement of climate-smart agriculture and offers practical insights for future food system resilience.

1. Introduction

Modern agriculture faces increasing challenges in responding to climate change, land degradation, and population growth. Traditional cultivation methods struggle to keep pace with demand while preserving environmental balance. Controlled Environment Agriculture (CEA) offers an alternative by creating optimal microclimates for plant growth in enclosed systems. Among recent innovations, rotating plant growth systems represent a leap forward in maximizing productivity per unit area, especially in urban or limited-space settings.

Modern agriculture is a dynamic sector at the intersection of technological progress, economic changes, and environmental requirements. Europe continues to be an example in promoting an innovative and sustainable agricultural model in a world facing increasingly complex global challenges. However, long-term success depends on the ability to integrate adaptable solutions that respond to the needs of a growing global population and protect the planet's limited resources [1,2].

In recent decades, conventional agriculture has faced mounting challenges stemming from climate change, urbanization, land degradation, and the depletion of freshwater resources. Traditional open-field farming methods, while historically effective, are increasingly constrained by unpredictable weather patterns, limited arable land, and rising input costs. Simultaneously, global population growth and urban expansion are generating unprecedented demand for fresh, local, and sustainably produced food. These pressures underscore the urgent need for alternative agricultural models that decouple food production from land availability and climatic variability. In this context, vertical farming—particularly in its high-efficiency, controlled-environment forms—has emerged as a viable and scalable solution to ensure resilient, year-round crop cultivation within or near urban centres [3-12].

While conventional agriculture has served humanity for millennia, it is increasingly challenged by environmental degradation, land scarcity, and climatic unpredictability. Vertical farming, on the other hand, offers an innovative solution through controlled-environment agriculture, yet introduces its own set of technological and economic considerations. The following figure presents a side-by-side comparison of the two systems across critical dimensions such as space use, water efficiency, energy demand, labour, productivity, and environmental impact [8-16].

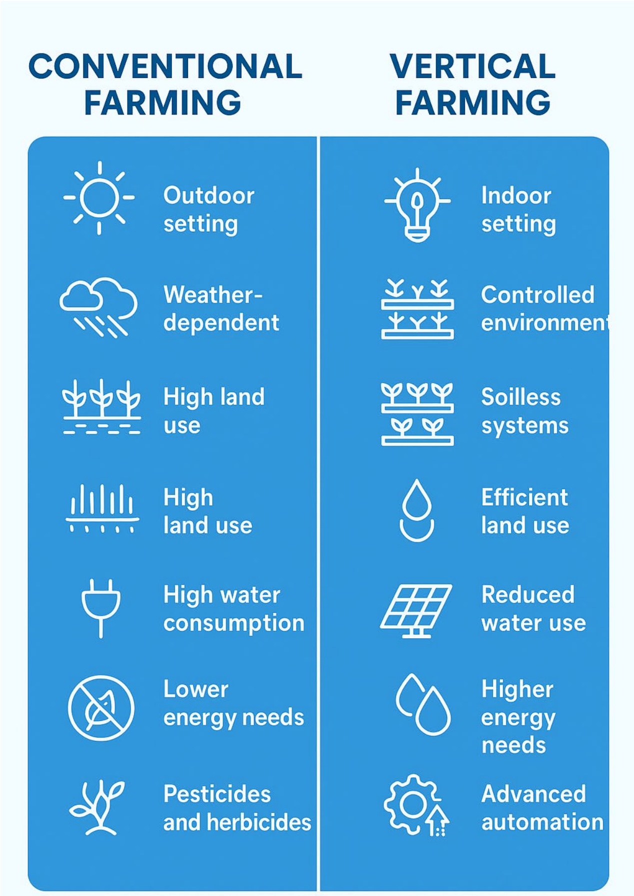

Figure 1. Comparison between conventional and vertical farming

Vertical farming significantly outperforms conventional agriculture in terms of spatial efficiency, water conservation, and crop cycle predictability. It minimizes the need for pesticides, reduces transportation emissions through urban proximity, and enables year-round cultivation. However, these benefits are offset by higher energy consumption, particularly for artificial lighting and climate control, as well as elevated initial capital costs. Conventional agriculture remains more accessible and energy-efficient in certain climates but is increasingly vulnerable to external pressures such as drought, pests, and land degradation. These comparisons underscore the need for a balanced, context-driven integration of both systems to ensure food security and environmental sustainability in the face of global change.

The aim of this paper is to present a new technological approach to conventional agriculture as well as to the already traditional vertical shelved vertical systems, by presenting the advantages and constraints of rotating plant growth systems, in the context of climate changes and population growth and migration towards cities.

2. Climate changes effects on agriculture

Agriculture in the European Union faces several serious challenges in the coming decades: competition for water resources, increased costs due to environmental protection policies, competition in international markets, loss of comparative advantage compared to international producers, climate change and associated physical factors, and uncertainties regarding the effectiveness of current European policies as adaptation strategies.

Table 1 highlights the climatic and physical factors relevant to global agricultural production, including sea level rise, CO_2 concentrations, and soil erosion, which, influenced by climate change, have a significant impact on agricultural productivity [4]."
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Table 1. Climate change and associated factors relevant to global agricultural production [4]

Climate and related physical factors	Expected direction of change	Potential impacts on agricultural production	Confidence level of potential impact
Atmospheric CO_2	Increase	Increased biomass production and potential increase in physiological water use efficiency in crops and weeds Altered hydrological balance of soils due to altered C/N ratio Altered weed ecology with potential for increased weed competition with crops	Average
		Agro-ecosystem modification	High
		N cycle change	High
		Yield increase lower than expected	Low
Atmospheric O_3	Increase	Declining crop yields	Low
Sea level	Increase	Sea level intrusion into coastal agricultural areas and salinization of water supplies	High
Extreme events	Poorly known, but significant increase in temporal and spatial variability expected Increased frequency of floods and droughts	Crop failure Yield decline Competition for water	High
Precipitation intensity	Intensified hydrological cycle, but with regional variations	Changed erosion and accretion patterns Changed storm impact Changed occurrence of flooding and storm damage	High

		Increased water storage Increased pest damage	
Temperature	Increase	Changes in crop suitability and productivity Changes in weeds, pests and crop diseases Changes in water requirements Changes in crop quality	High
Temperature	Day-night temperature differences	Changes in crop productivity and quality	Average
Thermal stress	Increases in heat waves	Damage to grain formation, growth of some pests	Average

"According to [5], climate change has a significant impact on agriculture, affecting crop productivity, water resource availability, and economic competitiveness. In the context of global warming of 1.5°C or 2°C, a considerable decline in agricultural yields is expected, especially in southern regions where reduced precipitation and limited access to irrigation exacerbate losses. Maize, a crop dependent on irrigation, is particularly vulnerable, while wheat in northern Europe could partially benefit from increased precipitation and CO_2 concentrations, although these advantages are limited by other factors."

Adapting agriculture to new climate conditions is essential and may include measures such as using more resilient crop varieties, adjusting sowing dates, and expanding irrigation infrastructure. At the same time, rising global demand and market adjustments can help mitigate losses, in some cases providing a competitive advantage. Through proper management and proactive measures, agriculture can face climate challenges and ensure long-term sustainability.

Table 2 presents the impact of climate change on the productivity of various crops, as estimated by different models. It highlights significant variations in yields depending on the crop, location, and climate conditions. For example, increased CO_2 concentrations may temporarily enhance vegetative growth and seed production in crops such as rice, but heat stress and altered precipitation can reduce these benefits. Moreover, elevated CO_2 levels negatively affect the nutrient content—such as zinc and iron—in C3 crops and legumes. The table also highlights regional differences in productivity, caused by the varying growing conditions of crops [6].

Table 2. Climate change and associated factors relevant to global agricultural production [5]

Crop	Yield variation	Cause	Model used	Location
Corn, soybeans, cotton	Yield increase to 29-32℃ -30-46% by 2100 -63-82% by 2100	Slowest warming scenario Rapid warming scenario	Hadley III Model	USA
Cotton, sunflower, wheat	-2-9% by 2050	Medium-high and low GHG emissions	DAYCENT	Central Valley of California
Wheat	-6%	With each degree Celsius, the average temperature of the month increases	Global grid-based, local point-based statistical regression and field heating experiments	Multiple sites in the world
Rice	-3.5%			
Corn	-7.4%			
Soybean	-3.1% by 2100			

Rainfed corn	-23-34% by 2055	Increased variability in temperature and precipitation	Probability-based approach	Illinois central
Wheat	-2.1%	Annual temperature increase	Multimethod analysis with statistical regression	Eastern and Northern Europe
Barley	-9.1%			
Corn	-24.5%			
Corn	-5.8%			Sub-Saharan Africa
Sugar cane	-3.9%			
Drought-tolerant sorghum	+0.7%			Sub-Saharan Africa
Cassava	+1.7%			Sub-Saharan Africa
Wheat	-9%			Oceania
Rice	-3.7%	1℃ increase in average growing season temperature	Regression, Kendall-tau statistic, Pearson correlation	China
Wheat	-10.2%			
	-10-20%			
Corn	-5-13% if it occurred later in the season	Increased frequencies of extreme and warming weather events	SALUS crop model	NORTH Midwest USA
Wheat	-5-17% and -2-18% if it appeared early in the season			
Sorghum	-2.2%			
Soybean	-0.5%	Temperature increase	County-specific multiple linear regression model	Great Plains of the USA
Corn	+1.6%			

Climate change can affect the development and survival of pathogens, increasing crop susceptibility to pests, diseases, and weeds. While agricultural yields may increase in high and mid-latitudes, they are projected to decline in warmer regions. Rising temperatures favour pest proliferation, their migration, and the extension of their development season, leading to significant losses and higher pesticide costs.

Moreover, climate change can reduce the effectiveness of plant protection measures and promote plant diseases such as blight in rice and potatoes. The dynamics of crop-weed competition are also affected, with weeds becoming more competitive under elevated CO_2 conditions. The expansion of pest infestation areas—such as nematodes, aphids, and moths—is expected globally, with implications for food security and agricultural costs [7-10].

3. Climate change responses in agriculture

Climate change is undoubtedly one of the greatest challenges we face today, and its effects on agriculture are both evident and concerning. Rising temperatures, changes in precipitation patterns, and extreme weather events—such as droughts and floods—have a direct impact on agricultural production. These changes not only reduce yields but also affect water availability and the balance of agricultural ecosystems. In addition, the rapid spread of pests, diseases, and weeds—favoured by the new climatic conditions—further complicates the situation for farmers, putting pressure on food security [16-20].

It is true that higher concentrations of CO_2 in the atmosphere can, in the short term, stimulate photosynthesis and the growth of certain crops. However, in reality, this advantage is countered by factors such as heat stress, water scarcity, and weed competition. At the same time, high levels of tropospheric ozone affect yields, and the salinization of coastal soils—caused by rising sea levels—threatens agricultural resources in those regions. Extreme weather phenomena, such as heavy rainfall or prolonged droughts, can destroy crops during critical development stages, significantly reducing productivity [21-24].

In Europe, the effects of climate change vary from region to region. In the northern and central parts of the continent, crops such as wheat and rapeseed benefit from a longer growing season, bringing advantages in some areas. Conversely, southern regions—such as Romania—are heavily affected by drought, extreme temperatures, and reduced rainfall. In Romania, drought years like 2020 have led to dramatic declines in the production of wheat, maize, and sunflower—crops essential to the national agricultural economy [3,4].

Adapting to these climate changes is no longer just an option, but a necessity. Farmers need concrete solutions, such as the use of drought-resistant hybrids, adjustments to planting periods, and the expansion of irrigation systems. Furthermore, agriculture must become more sustainable, with practices that protect the soil and natural resources. It is crucial that these measures are supported by clear policies and long-term investments that help farmers cope with these challenges. Collaboration among researchers, authorities, and farmers may be the key to finding the best solutions.

In recent decades, the use of greenhouses has increased significantly due to their economic and technological advantages. Plastic greenhouses have emerged as an optimal solution for extending the growing season and increasing yields; however, their success largely depends on location, climatic conditions, and the technologies employed. Choosing the right location is essential for obtaining profitable production, as it influences production costs, crop quality, and transportation efficiency. Temperature, humidity, and solar radiation must be maintained within optimal parameters to ensure healthy crop development [25-28].

Different greenhouse models have been developed depending on the climate. In cold regions, high-tech glass-covered greenhouses equipped with advanced climate control systems are predominant, while in Mediterranean areas, plastic greenhouses are preferred for their affordability and ease of management. An effective alternative is screenhouses, which provide a moderate greenhouse effect and protect crops from external factors such as wind and heavy rain. In this context, energy efficiency has become a key objective, and new technologies such as geothermal energy and nutrient substrates have contributed to increased yields [29-32].

Protected agriculture continues to develop, relying on innovative technologies, the use of renewable energy sources, and the implementation of sustainable solutions to optimize yield and reduce environmental impact. The constant evolution of greenhouse cultivation methods, along with adaptation to new climatic and economic challenges, will play a vital role in ensuring efficient and sustainable long-term production [33,34].

Hydroponic systems offer rapid growth and efficient nutrient delivery but come with high initial costs and require technical expertise for operation. Rotating hydroponics addresses these challenges through an innovative cylindrical design that maximizes space utilization and automates the cultivation process [35,36].

Closed-loop rotating hydroponic systems with software monitoring and automatic adjustments have started to be developed, reducing human intervention and optimizing growing conditions. This technology has the potential to revolutionize agriculture by enhancing global food security through sustainable and efficient production [37].

A rotating hydroponic system (Fig. 2) is designed to maximize plant growth in limited spaces, usually featuring a cylindrical metal frame mounted on a wheeled support for easy mobility. A motorized central shaft ensures uniform rotation of the frame, providing equal exposure of the plants to growing conditions. To ensure circularity, a tray collects excess nutrient solution. The structure includes systems to ensure efficient nutrient flow. The cylindrical design allows for the organization of multiple growing stations—compartments where parameters such as light, temperature, and humidity are controlled for optimal plant development. This type of system optimizes both space and resources, allowing for the simultaneous cultivation of multiple plants within the rotating frame [32].

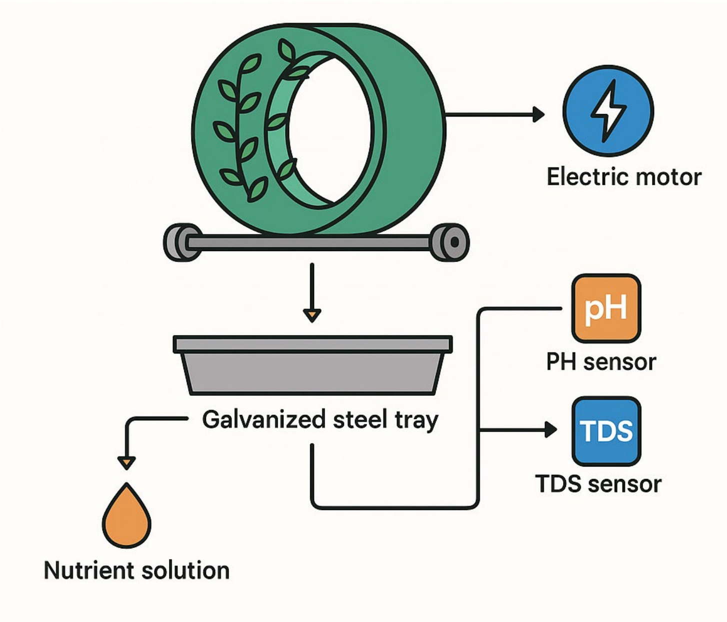

Figure 2. Operating diagram of a rotating plant growth systems

Advantages:

- Efficient use of space and nutrients
- Uniform exposure of plants to light and nutrient solution
- Full automation with pH and TDS monitoring
- Mobility due to the wheeled base.

Rotating hydroponics offers an efficient solution for food security and resource scarcity. The vertical design maximizes space utilization, allowing cultivation in areas with limited land. The system reduces water and nutrient consumption and can be automated, lowering labour requirements and increasing yield.

While both static and rotating vertical farming systems aim to optimize space, resource use, and productivity, their design, functionality, and operational outcomes differ significantly. The following comparative table provides a structured analysis of the two systems based on key performance criteria, drawing on recent studies in the field.

Table 3. Climate change and associated factors relevant to global agricultural production

Criterion	Rotating Vertical Systems	Conventional Vertical Systems
Space utilization	Highly efficient due to cylindrical design and continuous rotation [42].	Good, but vertical columns often leave central air space unused [38].
Light exposure	Uniform exposure enabled by rotation, minimizing shading and light competition [42].	Uneven light distribution; lower tiers often receive less light [38, 39].
Water and nutrient efficiency	Reduced consumption due to closed-loop recirculation [41].	Higher losses through drainage and evaporation if not automated [40].
Automation potential	High; integrates easily with sensors (pH, EC, temperature) and control systems [42].	Possible, but more common in large-scale commercial setups; less common in DIY systems [39].
Technological complexity	Complex; requires motorized rotation, programmable controls, and regular maintenance [42].	Low; simple mechanical construction with fewer failure points [38].

Initial investment	High due to mechanical and automation components [40].	Lower costs; suitable for low-budget or small-scale growers [39].
Scalability	Suitable for compact indoor environments; modular and space-optimized [41].	Scalable in greenhouses and vertical racks, but requires more horizontal space for higher output [39].
Reliability	Potential for mechanical wear; depends on quality of components [42].	Highly reliable with minimal mechanical risk [38].
Productivity	Higher per unit volume due to controlled and uniform growth conditions [42].	Varies depending on tier positioning and microclimate differences [38].
Mobility	Often mobile due to wheeled base design, enhancing flexibility [42].	Usually static; fixed installations limit relocation potential [39].

Rotating vertical farming systems demonstrate significant advantages in terms of light distribution, water/nutrient efficiency, and spatial optimization. Their modular and automated nature aligns well with modern controlled-environment agriculture (CEA) systems. However, these benefits come at the cost of greater mechanical complexity and higher initial investment, which may limit adoption for small-scale or resource-constrained growers.

In contrast, conventional vertical systems offer greater simplicity and accessibility, making them more widespread in small urban gardens, schools, and community agriculture settings. Nonetheless, their performance can vary depending on system design and environmental control, and they may face limitations in maximizing yield per unit of space.

Ultimately, the choice between rotating and conventional vertical systems should be based on available resources, scale of operation, and technical capacity. Future integration of AI-driven monitoring and smart automation could help bridge the gap between cost and performance in both models.

4. Discussion

Rotating hydroponic plant growth systems demonstrate significant potential for addressing current challenges in urban agriculture, including space constraints, inconsistent environmental exposure, and resource inefficiency. By leveraging a cylindrical rotating structure, the system ensures uniform light distribution and consistent nutrient exposure across all plants, overcoming limitations commonly observed in static vertical or horizontal hydroponic systems [38,42].

One of the most compelling advantages of this system lies in its ability to maximize the productive volume of a controlled environment. Traditional vertical farms often underutilize central vertical space, while rotating systems exploit this axis by enabling continuous, symmetrical plant rotation. This innovation not only enhances space utilization but also facilitates microclimate homogeneity, contributing to more stable growth conditions and reducing inter-plant variability.

Moreover, the integration of automation components—including pH, EC (TDS), temperature, and humidity sensors—supports real-time system monitoring and precise environmental control. These features align with the principles of precision agriculture, minimizing waste while enhancing productivity [39,40]. Such automation significantly reduces labour input, making the system particularly attractive in contexts where skilled agricultural labour is scarce or costly.

Despite its strengths, the rotating hydroponic system is not without limitations. Its higher initial investment and technological complexity may pose barriers to adoption, especially in developing regions or small-scale farming operations. Additionally, the presence of moving parts introduces potential points of mechanical failure, necessitating regular maintenance and specialized technical knowledge for troubleshooting and repairs.

From a broader perspective, the system aligns well with EU and global sustainability objectives, particularly those targeting reduced water use, minimized agrochemical inputs, and climate-resilient crop production [3, 4]. When integrated with renewable energy sources and AI-based crop management tools, rotating systems could serve as foundational modules in decentralized, off-grid food production systems suitable for urban rooftops, desert environments, or even space missions.

In terms of research opportunities, further work is needed to evaluate system performance across a wider range of crops, particularly those with different root architectures or canopy behaviours. Additionally, a comparative life cycle assessment would provide valuable insights into the environmental and economic trade-offs between rotating, static, and conventional soil-based systems.

5. Conclusions

Rotating hydroponic plant growth systems represent a technologically advanced, resource-efficient, and scalable solution for sustainable food production in controlled environments. Their ability to optimize space, automate cultivation, and reduce water and nutrient consumption makes them well-suited for urban agriculture, particularly in areas with limited arable land or harsh climate conditions.

Despite requiring higher capital investment and technical oversight, the benefits in terms of yield stability, system control, and long-term sustainability position these systems as a viable component of next-generation agriculture. As climate variability and population growth continue to pressure food systems, the deployment of rotating hydroponics—supported by policy incentives and technological innovation—may significantly contribute to resilient, decentralized food production.

Future research should focus on lifecycle analysis, energy consumption optimization, crop-specific performance, and economic feasibility assessments across diverse operational contexts. Additionally, integrating AI and IoT technologies may further improve system efficiency, enhance monitoring, and reduce manual labour needs, pushing rotating systems closer to autonomous food production units.

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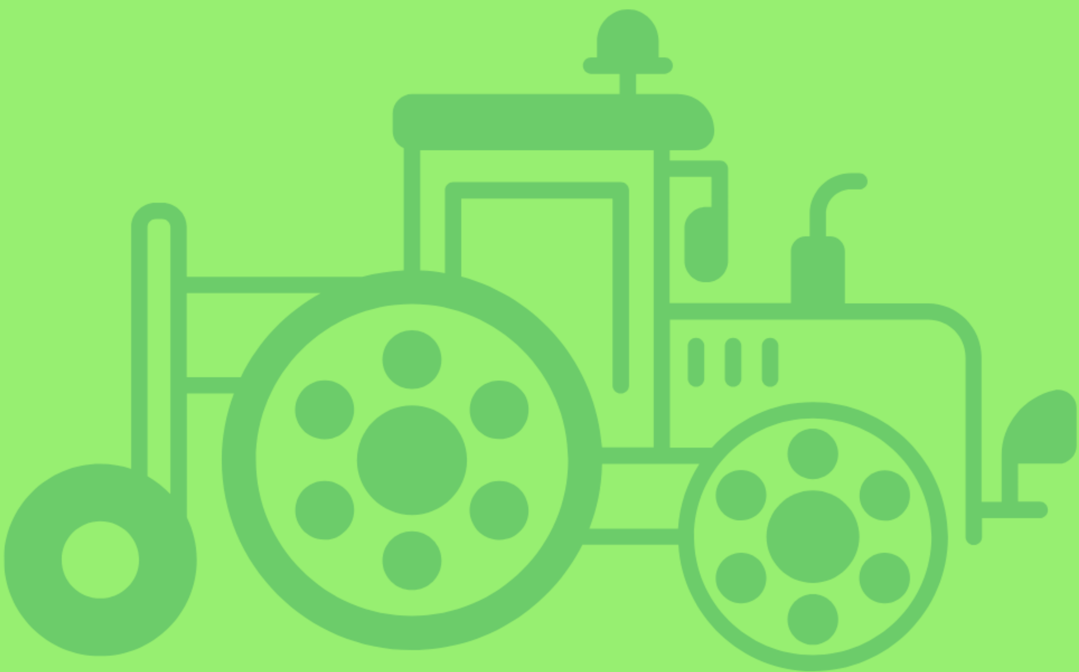

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