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Institute for Plant Protection and Environment, Belgrade, Serbia**

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"GREEN TRANSFORMATION OF AGRIBUSINESS: INNOVATION AS THE KEY TO
SUSTAINABLE AGRICULTURE"**

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FOREWORD

The Green Transformation of Agriculture is a development strategy aimed at building a modern, resource-renewable, and economically competitive agriculture. By turning contemporary ecological and climate challenges into development opportunities, an innovative “green technology” enables the improvement of agribusiness and self-sustainability. This process encompasses a series of development projects and initiatives focused on modernizing agriculture in less developed regions, strengthening the competitive position of domestic farmers, and connecting them to broader markets. A special emphasis is placed on preserving local plant varieties and indigenous animal breeds, as well as traditional products, while enhancing a cooperation among the scientific community, farmers, and all participants in the food chain.

Today, consumers are largely disconnected from food producers, and agribusiness is increasingly concentrated in the hands of large corporations, leading to population migration from rural areas. Therefore, investments in innovation and the smart integration of new technologies are key prerequisites for the development of small-scale agribusinesses, strengthening their competitiveness, and sustaining rural communities. Sustainability of agricultural production in rural areas and preservation of farmers’ position require the modernization of food production, implementation of new climate-adapted technologies, and establishment of efficient networks of all participants in the food production chain. The scientific community, farmers, policymakers, processors, and consumers must be interconnected and aware that only together can they address the increasingly complex challenges of contemporary agriculture.

Digitalization and green transformation, if implemented thoughtfully and inclusively, can contribute to the development of agribusiness and the production of safe food within a value chain where all participants have clearly defined roles. Innovations must not marginalize farmers or diminish their key role in production; instead, they should serve as tools for empowerment. By caring for human and animal health, preserving the environment, using pesticides and fertilizers rationally, transitioning from conventional to organic and regenerative production, managing natural resources responsibly, and reducing greenhouse gas emissions, we ensure a healthy and sustainable planet for future generations.

In this context, this scientific gathering aims to bring researchers, experts, policymakers, and practitioners together to exchange the latest scientific findings, innovative solutions, and examples of good practice in sustainable agriculture. Special emphasis is placed on an interdisciplinary approach, the application of modern technologies, knowledge transfer, and strengthening the capacities of local communities, while respecting the principles of sustainable development. The papers presented in this collection contribute to a better understanding of the process of green transformation in agriculture and provide relevant scientific and practical guidelines for its further development in both regional and international contexts.

We extend our sincere gratitude to everyone who has contributed to the successful realization of the 13th **JEEP INTERNATIONAL SCIENTIFIC CONFERENCE ON AGRIBUSINESS MAK 2026**, entitled “*Green Transformation of Agribusiness: Innovations as the Key to Sustainable Agriculture.*” We would like to thank the authors of the papers, all the participants who have taken part in constructive discussions, and all collaborators who have offered multiple perspectives on contemporary agricultural challenges, proposed solutions, and encouraged a responsible approach to the environment, food production, and human health.

Danijela Šikuljak, Ph.D. Principal Research Fellow
Prof. Snežana Janković, Ph.D. Principal Research Fellow

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SOIL DEGRADATION IN THE WORLD, SERBIA AND MONTENEGRO: CAUSES, CONSEQUENCES, AND POSSIBLE SOLUTIONS

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Abstract: This study investigates the primary causes of soil degradation globally, but also in Serbia and Montenegro, as well as their ecological and socio-economic consequences, with a particular emphasis on potential mitigation and remediation strategies. Soil degradation is analysed because of its substantial impact on biodiversity, sustainable development, and agricultural productivity. The research aims to assess the extent to which natural and anthropogenic factors contribute to soil quality decline. The methodology involves a review of relevant scientific and professional literature and the analysis of statistical data from international and national institutions, with a focus on the past two decades and on agricultural and erosion-prone regions. Findings indicate that erosion, unsustainable farming practices, urbanisation, and climate change are principal drivers of soil degradation both globally and in Serbia and Montenegro. The study concludes that adopting sustainable soil management practices, strengthening the legal framework, and enhancing public awareness could substantially mitigate the negative effects of soil degradation. The main limitations concern the availability and timeliness of data for certain regions.

Keywords: Soil degradation, Erosion, Sustainable management, Climate change, Serbia, Montenegro

INTRODUCTION

Soil degradation is a key constraint on sustainable development, food security and ecosystem stability at the global scale. Driven by the combined effects of land-use change, inappropriate agricultural practices, pollution and accelerating climate change, the loss of soil quantity and quality is now documented across all continents and a wide range of agro-ecological zones. In the Western Balkans, and particularly in Serbia and Montenegro, this process is further conditioned by pronounced relief, mountain karst geomorphology, and the limited extent of high-quality agricultural land, which together make soils highly vulnerable to erosion and structural decline. Despite growing international attention, there remains a need to synthesise global knowledge with region-specific evidence to understand better how natural and anthropogenic factors interact to shape degradation patterns and their ecological and socio-economic impacts. This paper therefore analyses the main drivers, consequences and potential mitigation and remediation options for soil degradation at the global level and in Serbia and Montenegro, with comparative reference from the Global to the local level.

MATERIAL AND METHODS

The study is based on a desk-based synthesis of scientific and professional literature, supported by data from international (FAO, UNCCD, FAOSTAT, etc.) and national institutions in Montenegro and Serbia. Priority was given to sources from the last two decades and to studies focused on agricultural and erosion-prone areas. The analysis proceeded in three steps: (i) identification and classification of the main drivers and forms of soil degradation at the global scale and in Montenegro and Serbia; (ii) comparative assessment of ecological and socio-economic consequences, with particular emphasis on erosion, loss of soil organic carbon and climate-related stress; and (iii) evaluation of proposed mitigation and remediation measures, structured through a comparative matrix and SWOT framework. The approach is qualitative and integrative, aiming to link global findings with region-specific evidence rather than to develop new quantitative models or field measurements.

RESULTS AND DISCUSSION

Leading Causes of Soil Degradation Worldwide

The literature consistently identifies soil degradation as a globally pervasive process driven by human-induced land-use change, unsustainable agricultural practices and climate-related stressors. The Status of the World's Soil Resources report (FAO and ITPS, 2015) indicates that most global soils are in fair to poor condition, with accelerated erosion, organic-matter decline, nutrient imbalance, salinisation, acidification, contamination and biodiversity loss among the dominant threats to soil and ecosystem services (FAO and ITPS, 2015; JRC, 2024).

A leading global driver of erosion is accelerated erosion by water and wind, which removes fertile topsoil, reduces soil depth and productivity, and produces major off-site impacts through sedimentation and water-quality deterioration (Pimentel, 2006; Billi and Spalevic 2022). Erosion is especially severe on sloping terrain, on sparsely covered soils, and on intensively cultivated land, and in many regions, it proceeds far faster than natural soil formation (FAO and ITPS, 2015; Pimentel, 2006; Spalevic, 2011; Spalevic et al., 2014). Recent global modelling also shows that cropland expansion and land-use change in the 21st century have further intensified erosion risks in several world regions.

Closely linked to erosion is the decline in soil organic carbon (SOC). Converting natural ecosystems to cropland, removing residues and practising intensive tillage reduce organic inputs and accelerate mineralisation, leading to losses of soil structure, fertility and biological activity. SOC depletion is widely recognised as a key indicator of land degradation, with major implications for agricultural productivity and the global carbon cycle (Lal, 2015). Many agrarian systems also face nutrient depletion and elemental imbalance, where nutrient export through harvesting and erosion is not compensated for by replenishment. This long-term nutrient mining lowers crop productivity and reduces soil resilience, particularly in marginal and smallholder systems (FAO and ITPS, 2015).

In mechanised production zones, degradation is manifested as soil compaction and structural decline caused by heavy machinery and repeated tillage, which restrict rooting,

reduce infiltration and reinforce cycles of low biomass return. In irrigated and arid regions, salinisation is a widespread problem resulting from inadequate drainage and poorly managed irrigation, leading to altered soil structure, reduced plant growth and significant productivity losses (Shokri et al., 2024). In other areas, acidification arising from inappropriate fertiliser use and land-use transitions decreases nutrient availability, increases metal toxicity, and limits soil biota functioning and crop performance.

Further degradation pressures arise from pollution and contamination associated with industry, mining, waste disposal, pesticides and heavy metals, creating localised but severe hotspots with long-term ecological and health risks. Multiple studies also document losses of soil biodiversity and biological functioning, linked to erosion, SOC decline (Lal, 2015), pollution and land-use intensification, which weaken nutrient cycling and reduce ecosystem resilience.

Finally, land-use change and deforestation act as cross-cutting drivers that amplify erosion, SOC loss and hydrological instability, while climate-change-related stressors, such as warming, extreme rainfall, droughts and increasing aridity, accelerate ongoing degradation and increase the risk of desertification (JRC, 2024). Taken together, the evidence shows that global soil degradation results from the cumulative interaction of biophysical processes and human pressures, with regional variability but broadly convergent trends towards erosion-driven topsoil loss, organic-matter decline, structural degradation, and growing vulnerability under climate change (FAO and ITPS, 2015).

Leading Causes of Soil Degradation in Montenegro

Soil degradation in Montenegro is largely shaped by its mountainous and karst geomorphology, where shallow, erosion-prone soils dominate steep terrain with discontinuous cover. Many soils formed on limestone and dolomite have shallow rooting depth, are drought-sensitive and have limited production potential. Across mountain regions, water erosion is a leading driver, intensified by steep relief, seasonal heavy rainfall and sparse vegetation, resulting in soil thinning, bedrock exposure and fragmentation of arable land (Spalevic, 2024).

A considerable part of the territory comprises land with low or limited agricultural fertility (VII-VIII capability classes), while deeper, more productive soils are largely restricted to river valleys, terraces and karst poljes. In upland rural regions, overgrazing and grazing pressure on natural grasslands and pastures contribute to vegetation degradation, reduced ground cover and accelerated erosion. At the same time, demographic decline and the abandonment of marginal agricultural land increase exposure to erosion and slope instability on already fragile soils. Degradation is intensified where unsuitable cultivation is practised on shallow or steep terrain, including mechanised tillage on discontinuous soils and former terrace systems, which disturb soil structure, reduce organic-matter inputs and increase susceptibility to runoff and topsoil loss (Spalevic, 2024; Hamza and Anderson, 2005).

In contrast, the limited areas of deeper, more fertile soils in valley and coastal plains are increasingly exposed to urbanisation and infrastructure expansion, causing fragmentation and the permanent loss of high-value agricultural land. Climate stress further accelerates

degradation: drought reduces vegetation cover, while intense rainfall increases runoff and erosion on steep, shallow soils. Overall, soil degradation in Montenegro arises from the interaction of natural constraints (relief, karst and shallow soils) with human and climate-induced pressures, with erosion and soil shallowing as the dominant outcomes.

Leading causes of soil degradation in Serbia

Evidence from national assessments indicates that soil degradation in Serbia is driven by the combined effects of hydrometeorological extremes, erosion, land-use transitions, agricultural management practices and climate-related stressors (UNDP and MEP, 2022). Among all forms of degradation, water erosion is the most widespread and severe driver, strongly intensified by recent increases in extreme precipitation, high-intensity rainfall and flood events. These processes enhance surface runoff, soil detachment and downslope sediment transport, particularly in hilly and mountainous terrain and in river catchments exposed to torrential flows.

A major accompanying degradation pathway is the decline in soil organic carbon (SOC), driven by land-use change, residue removal, intensive tillage and insufficient organic-matter return to soil. SOC depletion weakens soil structure, increases erodibility, reduces infiltration and lowers resilience to climatic stresses, thereby amplifying erosion and productivity loss (Hamza and Anderson, 2005). Degradation risk is further increased by the overexploitation and mismanagement of agricultural soils, including intensive mechanisation, repeated soil disturbance and inadequate nutrient restoration, which lead to structural deterioration, compaction and reduced soil functionality (Hamza and Anderson, 2005; Vidojević, 2024).

In marginal rural areas, the abandonment of agricultural land leads to vegetation loss and disrupted ground cover, increasing exposure to erosion and slope instability in already vulnerable landscapes. Land-use change and conversion also transform previously stable soil systems, increasing their sensitivity to hydrological extremes and climate pressures, particularly when interventions are unplanned or inappropriate.

Climate change globally acts as a cross-cutting degradation accelerator through rising temperatures, increased aridity during the vegetation period, more frequent and prolonged droughts, and intensified extreme-rainfall events (UNDP and MEP, 2022; JRC, 2024). These changes collectively increase the risk of both erosional degradation and desertification-type processes, with projections indicating that a substantial part of the territory of Serbia may shift into moderate-to-high degradation-risk classes by mid-century.

In the northern lowland region of Vojvodina, degradation is also evident through wind erosion on open agricultural fields, especially during dry periods and bare-soil stages, when the combination of drought, strong winds and reduced ground cover leads to significant loss of topsoil and nutrients, with documented implications for productivity and air quality. Finally, local industrial and urban pollution contributes to degradation in specific zones, adding contamination pressures to soils already affected by structural decline, erosion and organic-matter loss.

Taken together, these processes indicate that soil degradation in Serbia is shaped by the interaction of erosion, SOC decline, land-use change, inadequate soil management and climate-driven stress, with water and wind erosion emerging as the dominant and mutually reinforcing drivers.

Ecological Consequences of Soil Degradation, World

Evidence from global assessments indicates that soil degradation has profound ecological consequences, primarily through the loss and impairment of key ecosystem services: food provision, water regulation and climate buffering. Degraded soils show reduced fertility, diminished biological productivity and disrupted regulation of water and nutrient cycles, which collectively undermine crop yields, increase food-insecurity risk and weaken ecosystems' capacity to support biodiversity and climate-regulating functions. A central demonstration of these changes is the decline in soil organic carbon (SOC), which reduces the soil's carbon-sink capacity, increases CO₂ emissions, weakens soil structure, lowers water-retention capacity and increases erodibility and vulnerability to drought and extreme rainfall.

Soil degradation is also closely linked to biodiversity loss in soil biota and terrestrial habitats, as declines in microbial, faunal and plant diversity disrupt soil food webs, reduce functional redundancy and diminish ecosystem resilience and recovery potential under environmental stress (Bardgett and van der Putten, 2014). In general, these processes are directly linked to alterations in nutrient and biogeochemical cycles (nitrogen, phosphorus and carbon), affecting vegetation productivity, water quality and greenhouse-gas exchange (Bardgett and van der Putten, 2014). Hydrological functioning is reduced: compaction, structural decline and organic-matter loss reduce infiltration, increase surface runoff and flood risk, and limit groundwater recharge and the water-regulating capacity of landscapes. Intensified erosion results in greater sediment delivery to rivers, coastal systems, degrading habitats, increasing turbidity and contributing to eutrophication and downstream ecological stress.

In dryland regions, degradation often manifests as desertification and land aridification, characterised by vegetation decline, soil crusting, loss of biological productivity, and the expansion of sparsely vegetated or barren areas. These transformations reduce ecosystem resilience and increase exposure to drought, wind erosion, and dust emissions. Across many landscapes, soil loss, vegetation decline, and nutrient depletion create positive feedback loops of degradation, in which reduced plant cover accelerates erosion, which in turn depletes soil resources and weakens ecosystem recovery capacity.

Taken together, global evidence demonstrates that soil degradation drives a systemic decline in ecological services, from food provision, biodiversity support and climate regulation to hydrological stability and landscape resilience, with cascading impacts across terrestrial and aquatic ecosystems at local, regional and global scales (Bardgett and van der Putten, 2014).

Ecological Consequences of Soil Degradation in Montenegro

Closely linked to the country's predominantly mountainous and karst relief, where steep slopes, shallow soils and discontinuous vegetation cover create conditions for rapid, cumulative environmental impacts. On steep karst and mountain slopes, accelerated erosion progressively removes and thins the already shallow soils, exposing bedrock and reducing effective rooting depth. This, in turn, diminishes vegetation productivity, reduces landscape stability, and weakens ecosystem functioning. These effects are particularly pronounced in low- or limited-agricultural-fertility land (VII-VIII capability classes), where additional soil loss further reduces biological productivity and reinforces long-term ecological constraints.

In upland rural areas affected by depopulation and land abandonment, the disruption of traditional land management leads to landscape instability and secondary erosion, especially where vegetation regrowth is insufficient to protect fragile slopes. In karst environments, soil thinning and limited water-retention capacity contribute to the degradation of karst ecosystems, altering microhabitats, reducing moisture availability, and limiting the ability of soils and vegetation to buffer hydrological fluctuations. Overgrazing on pastures and grasslands accelerates the loss of pasture productivity and grassland biodiversity, as reduced ground cover increases erosion susceptibility and simplifies plant communities.

Soil degradation also increases the sensitivity of Montenegrin ecosystems to climate variability: episodes of extreme rainfall intensify runoff and slope instability, while periods of drought reduce vegetation cover and biological activity, further amplifying erosion risks on shallow and skeletal soils. At the same time, fertile valley soils and karst poljes are exposed to urbanisation and infrastructure pressure, resulting in the loss of natural and semi-natural land and the permanent loss of ecologically valuable soil resources in the most productive parts of the landscape.

Taken together, these processes demonstrate that in Montenegro's fragile mountain and karst environments, even relatively small soil losses can translate into disproportionately large ecological impacts, affecting vegetation structure, habitat continuity, hydrological functioning, and long-term landscape resilience.

Ecological Consequences of Soil Degradation in Serbia

Arise primarily from the widespread impacts of erosional processes, organic-matter decline and increased exposure to climate-related extremes. The most prevalent effects are associated with water erosion, which leads to progressive soil loss, sedimentation and disturbance of river channels, floodplains and associated wetland ecosystems, thereby reducing their hydro morphological and ecological functioning. Closely linked to these processes is the decline in soil organic carbon, which weakens soil structure, reduces biological productivity and lowers the capacity of soils to retain water and nutrients, diminishing ecosystem performance and resilience.

Reduced infiltration capacity, combined with more frequent extreme precipitation events, increases surface runoff, raises flood risk, accelerates erosion, and limits groundwater

recharge and the water-regulating functions of soils. Under climatic warming, parts of Serbia face an intensified risk of aridity and desertification-type processes, particularly in regions exposed to prolonged drought and increasing moisture deficits. In the northern lowland areas, especially in Vojvodina, degradation is further manifested through wind erosion, which leads to dust emissions, loss of fine particles and nutrients, and adverse effects on air quality and agro-ecosystem stability during dry, bare-soil periods.

These processes collectively result in a loss of agricultural ecosystem resilience, as evidenced by lower drought tolerance, greater yield variability, and reduced capacity of production systems to absorb climatic shocks. The decline of organic matter and soil biological activity contributes to the degradation of soil biodiversity, weakening nutrient cycling and ecosystem functioning. In addition, localised contamination hotspots near industrial and urban areas introduce further ecological and health risks in already vulnerable environments. Overall, national assessments emphasise that climate change acts as a key intensifying factor, intensifying nearly all degradation-linked ecological impacts by reinforcing erosion dynamics, accelerating organic-matter decline and increasing the frequency and severity of hydrometeorological extremes across Serbia's landscapes (UNDP and MEP, 2022).

Socio-economic Consequences of Soil Degradation, World

Global evidence indicates that soil degradation has substantial socioeconomic implications that extend beyond the agricultural sector, affecting livelihoods, rural development, public finances, and broader economic stability. One of the most direct impacts is a reduction in farm productivity and food security, reflected in declining yields, higher crop-failure risk and rising production costs, which lead to lower farmer incomes and increased vulnerability of rural incomes, particularly among smallholders and communities in developing regions. As soil fertility declines and structural degradation intensifies, farmers increasingly depend on higher levels of fertilisers, irrigation and other land inputs to compensate for fertility loss, raising financial burdens and widening inequality between capital-intensive and resource-poor farming.

At the macro scale, soil degradation contributes to the loss of natural capital and ecosystem service value, including diminished water regulation, climate buffering, erosion control, and flood protection, functions that support both rural and urban societies. Degraded landscapes also experience greater exposure to disasters such as floods, landslides and drought-related losses, as reduced infiltration, slope instability and weakened ground cover increase the frequency and severity of damaging events. In many regions, these processes are associated with rural poverty, land abandonment and migration pressures, particularly in marginal environments where declining productivity and repeated economic stress lead to depopulation and social restructuring.

For governments, soil degradation increases public expenditure on land restoration programmes, the rehabilitation of damaged infrastructure, disaster recovery measures, and environmental protection initiatives. Taken together, the cumulative impacts of soil degradation create a negative feedback loop within national economies, undermining agricultural GDP, weakening food-system stability, and constraining long-term development potential. Overall, the literature indicates that soil degradation is not only an

environmental challenge but also a systemic socio-economic risk with far-reaching implications for public welfare and sustainable economic growth at the global scale.

Socio-economic Consequences of Soil Degradation: Montenegro

Strongly conditioned by the country's fragile mountain and karst environments and by the limited extent of productive soils. Reduced productivity on already shallow, low-fertility soils lower agricultural output and farm profitability, particularly in marginal upland areas where production potential is inherently constrained. On steep, erosion-prone terrain, continued soil loss reduces usable land, limiting opportunities for rural development and narrowing land-use options for local communities. These processes are closely linked to depopulation and the abandonment of marginal rural areas, where low economic returns and declining land productivity contribute to out-migration and ageing settlements.

At the same time, erosion, slope instability and surface runoff increase maintenance and protection costs for rural infrastructure, affecting roads, terraces, retaining structures and other assets that require frequent repair or stabilisation. Because fertile valley soils and karst poljes are scarce and highly valuable resources, they are increasingly exposed to urbanisation and land-use competition between agriculture, tourism and construction, leading to permanent loss of high-quality soils and constraining future agricultural development. In upland pastoral systems, soil degradation and erosion reduce pasture quality and livestock carrying capacity, resulting in economic losses for households dependent on grazing-based production.

These vulnerabilities are further intensified during climate extremes, when droughts and episodes of intense rainfall increase economic damage to land, production systems and infrastructure. Despite the relatively small absolute area of degraded land, the combination of fragile terrain, limited agricultural resources and the concentration of fertile soils means that soil degradation in Montenegro exerts disproportionately high socio-economic impacts on rural livelihoods and regional development.

Socio-economic Consequences of Soil Degradation: Serbia

The socio-economic consequences of soil degradation in Serbia are closely linked to the combined effects of erosion, declines in soil organic carbon and intensifying climate stress. The most direct outcomes are yield reduction and a loss of agricultural income, as declining soil fertility, structural degradation, and recurrent hydrometeorological extremes reduce productivity and increase production variability. In response, farmers face higher costs for soil rehabilitation, irrigation and nutrient inputs as they attempt to compensate for deteriorating soil quality and maintain acceptable yield levels. Frequent episodes of flooding, runoff and extreme precipitation cause additional damage to farmland, settlements and rural infrastructure, generating repeated recovery costs and increasing economic vulnerability. In climatically sensitive regions, degradation increase the risk of desertification and land-use restrictions, thereby limiting economic use, investment, and long-term development opportunities.

In Vojvodina's northern lowland region, soil degradation is evident through wind erosion, including the loss of fine soil particles, nutrient leaching, dust events, and reduced crop

value, as well as negative impacts on air quality and agroecosystem stability. At a broader scale, these interacting pressures weaken the resilience of rural economies to climate shocks, resulting in greater production instability and greater household vulnerability. For the public sector, soil degradation involves increasing expenditures on monitoring, land restoration, disaster response, and adaptation planning, particularly in erosion-prone and flood-affected catchments. National assessments emphasise that climate change multiplies socio-economic risks by accelerating existing degradation trends and increasing the frequency and severity of damaging events across rural systems in Serbia.

Potential Mitigation and Remediation Measures: World

The global literature highlights a broad range of mitigation and remediation measures that can slow, halt, or reverse soil degradation while restoring ecosystem services and production capacity (Lal, 2015). A central pillar of sustainable land management is the implementation of conservation and regenerative agriculture, including reduced- or no-tillage systems, permanent soil cover through mulching, crop residues or cover crops, and diversified crop rotations and intercropping, which enhance soil structure, increase organic matter inputs, reduce erosion, and improve water-use efficiency. A key pathway for improving long-term soil quality is the restoration of the soil organic carbon (SOC) pool, supported by residue retention, the application of manure and compost, the targeted use of biochar in degraded or sandy soils, and the expansion of agroforestry and agro production systems, which strengthen soil fertility, biological activity, and structural stability.

Complementary measures should focus on erosion control, including contour farming, strip cropping and terracing, together with vegetative buffer zones, riparian belts, and the stabilisation and revegetation of gullies, thereby reducing sediment loss and protecting downstream ecosystems. Improved soil performance also depends on balanced and integrated nutrient management, combining soil testing and site-specific fertilisation strategies with the integration of organic and mineral nutrient sources to maintain positive nutrient balances and prevent depletion and pollution. In areas affected by chemical degradation, targeted actions for salinity and acidity management, such as improved drainage and leaching management, gypsum application where appropriate, and liming of acid soils, contribute to the recovery of soil functionality and plant growth (FAO and ITPS, 2015).

Mitigating contamination requires strengthening pollution-prevention and remediation frameworks, including stricter industrial and mining controls, as well as site-specific measures such as phytoremediation and the removal of contaminated soil in critical hotspots (Lal, 2015). At broader spatial scales, landscape-level restoration, through reforestation and afforestation of fragile slopes, rangeland rehabilitation and controlled grazing regimes, supports erosion reduction, biodiversity recovery and hydrological regulation. Finally, long-term progress depends on effective monitoring and governance mechanisms, including integrated soil-monitoring systems, early-warning tools and incentive schemes such as payments for ecosystem services and soil stewardship programmes, which promote the adoption of sustainable management practices and support progress towards land-degradation neutrality at the global scale (JRC, 2024).

Potential Mitigation and Remediation Measures: Montenegro

Potential mitigation and remediation measures in Montenegro are shaped by the predominance of steep mountain and karst terrain, the shallow, erosion-prone nature of many soils, and the limited spatial extent of highly productive land. A key priority is erosion prevention on steep and karst landscapes, particularly in hilly agricultural zones, through contour planting and terracing, re-vegetation of bare and shallow soils, and targeted stabilisation of erosion hotspots, which help to reduce runoff, protect fragile slopes and prevent further soil thinning. In upland pastoral regions, sustainable pasture and grazing management, including rotating or controlled grazing and reseedling of degraded grasslands, supports the recovery of plant cover, improves pasture productivity and enhances the long-term ecological stability of upland landscapes.

Given the scarcity of productive soils, protecting fertile valley soils and karst poljes is a strategic measure, implemented through zoning to reduce urbanisation pressure and safeguard high-value agricultural land from irreversible loss and fragmentation. In areas of abandoned agricultural land, restoration approaches include natural succession or assisted afforestation, as well as transitions towards perennial or agroforestry systems that increase vegetation cover, improve soil structure and enhance organic-matter accumulation. On shallow, low-fertility soils, soil-fertility improvement measures, such as organic amendments, mulching and low-input conservation farming, strengthen soil resilience and reduce erosion susceptibility.

Montenegro is exposed to hydrometeorological extremes, climate-resilience actions are also essential. This includes introducing drought-tolerant crops in drier regions and improving drainage and runoff-control measures in areas affected by intense rainfall. Finally, the effective targeting of mitigation actions depends on regional land monitoring and erosion modelling, which support the identification and prioritisation of high-risk mountain catchments and enable evidence-based planning of restoration and protection measures.

Potential Mitigation and Remediation Measures for Soil Degradation in Serbia

Focus should be on reducing erosion, restoring soil organic matter, improving farm management and boosting climate resilience. Priority measures include preventing water and wind erosion in hilly areas and Vojvodina's lowlands through contour and strip cropping, winter cover on fields, and shelterbelts and windbreaks to reduce runoff and soil loss. Restoring soil organic matter and soil organic carbon (SOC) plays a central role in improving soil structure, fertility, and climate resilience. Retaining crop residues, applying organic amendments and green manures, and adopting reduced-tillage systems support the build-up of organic matter and reduce erosion susceptibility. These practices are complemented by improved agricultural soil management, including avoiding over-exploitation and excessive residue removal, and diversifying crop rotations to stabilise yields and enhance soil biological activity (Borrelli et al., 2017; Khaleedi Darvishan et al., 2019).

At the territorial level, risk-based land-use planning is essential for limiting the conversion of relatively stable soils to more vulnerable land uses and for guiding development away

from flood- and slope-prone areas (Borrelli et al., 2017; Spalevic et al., 2013; Spalevic et al., 2014). Erosion-risk zoning enables prioritisation of protection and adaptation measures in landscapes exposed to accelerated runoff and geomorphological instability. Climate-related risks are addressed through drought-mitigation practices (mulching, conservation tillage) and runoff and flood-control measures in areas affected by extreme rainfall. Effective mitigation further requires stronger monitoring and early-warning systems, supported by integrated soil-degradation assessments that identify priority intervention areas and enable timely decision-making (Spalevic et al., 1999). Restoration of degraded land through assisted re-vegetation, agroforestry, and perennial cover supports the long-term recovery of soil functions, reduces erosion, and strengthens landscape resilience in Serbia. Table 1 summarises the dominant drivers, ecological and socio-economic consequences, and priority mitigation and remediation measures related to soil degradation at the global level and in Montenegro and Serbia.

Table 1. Comparison of Soil Degradation: Drivers, Consequences and Mitigation

Dimension	World	Montenegro	Serbia
Dominant drivers	Land-use change, unsustainable agriculture, erosion by water & wind, SOC decline, compaction, salinisation, acidification, pollution; climate stress as accelerator	Mountainous & karst relief, shallow soils, steep slopes, water erosion, overgrazing, land abandonment, unsuitable cultivation on fragile soils; urbanisation pressure in valleys; climate extremes	Water erosion (extreme rainfall & floods), SOC decline, intensive tillage & residue removal, land-use change & abandonment, wind erosion in Vojvodina; climate-driven aridity
Ecological consequences	Loss of ecosystem services; reduced fertility and productivity; SOC decline and increased CO ₂ ; biodiversity loss; disturbed nutrient and hydrological cycles; desertification and sedimentation; weakening of ecosystem resilience	Thinning of soil and loss; habitat fragmentation; degradation of karst ecosystems & poor water retention; pasture & biodiversity degradation; sensitivity to droughts & intense rainfall; loss of land in valleys	Soil loss & sedimentation; weakened soil structure & productivity; increased runoff & flood risk; aridity / desertification risk; wind-erosion dust & nutrient loss in Vojvodina; decline of soil biota & resilience
Socio-economic consequences	decreased yields and food security; increased production costs; lower farm income; disaster exposure; rural poverty, abandonment and migration; rising public restoration costs; negative feedback on GDP and food-system stability	decreased farm profitability; loss of usable land on steep slopes; rural depopulation & ageing; higher infrastructure maintenance costs; competition for scarce fertile valleys; decreased pasture capacity; climate-amplified damages	Yield & income losses; increased costs of irrigation & nutrients; flood damage to land & infrastructure; land-use limits in vulnerable regions; wind-erosion losses in Vojvodina; decreased rural economic resilience; increased costs

Priority mitigation / remediation	Conservation / regenerative agriculture; SOC restoration; contouring, terracing & buffers; integrated nutrient management; salinity / acidity treatment; pollution control; landscape-scale restoration; monitoring & governance incentives	Erosion prevention on steep & karst terrain; re-vegetation & hotspot stabilisation; sustainable grazing; protection of limited fertile valley soils; restoration of abandoned land; organic amendments & low-input farming; climate-resilience & catchment prioritisation	Prevention of water & wind erosion (contour / strip cropping, winter cover, windbreaks); SOC restoration (residues, organics, reduced tillage); diversified rotations; risk-based land-use planning; drought & runoff control; monitoring & re-vegetation / agroforestry

The SWOT comparison presented in Table 2 synthesises key strengths, weaknesses, opportunities and threats related to soil degradation and its management in the global context and in the specific environmental and socio-economic conditions of Montenegro and Serbia.

The results of the comparative and SWOT analyses indicate that, although the dominant drivers of degradation are broadly similar across scales, their impacts are considerably amplified in Montenegro and Serbia, particularly in fragile terrain, under land-use pressure, and amid intensifying climate extremes.

Table 2. Comparative SWOT Framework for Soil Degradation Drivers, Impacts and Responses

Strengths		
World	Montenegro	Serbia
Extensive scientific evidence base & global soil assessment frameworks	Clearly identified natural specificities (mountain-karst relief, shallow and erosion-prone soils)	Strong scientific and professional tradition in erosion and land degradation studies
Developed concepts for sustainable and regenerative soil management	Small territory enables targeted pilot restoration and management actions	Institutional network and experience with monitoring programmes
International initiatives and funding mechanisms (FAO, UNCCD, EU)	Recognised need to protect scarce fertile valley soils and karst fields	Presence of agronomic and planning measures for erosion reduction
Weaknesses		
World	Montenegro	Serbia
Large regional inequalities in data quality and management capacity	Limited extent of productive soils and dependence on mountain areas	Intensive agriculture with SOC decline and structural degradation
Slow implementation of sustainable land management policies	Rural depopulation & abandonment increase erosion exposure	Excessive tillage, residue removal and weak crop-rotation diversity
Expansion of land degradation faster than the mitigation capacity	Limited institutional and financial capacity for long-term monitoring	High exposure to floods and erosion in hilly and river-basin areas

Opportunities		
World	Montenegro	Serbia
Global shift toward <i>land-degradation neutrality</i> and climate-finance mechanisms	Strengthening protection of fertile valley soils through spatial planning and zoning	Scaling-up conservation agriculture and agroforestry practices
Expansion of regenerative farming and carbon-smart soil management	Pilot restoration of erosion hotspots and abandoned land	SOC recovery through organic amendments and reduced tillage
Rapid development of monitoring, modelling & remote sensing tools	Incentive schemes and PES mechanisms for farmers	Access to EU and regional funds for restoration of degraded land
Threats		
World	Montenegro	Serbia
Accelerating climate change leads to more droughts, extreme rainfall and degradation pressure	Urbanisation of valleys and karst fields leads to permanent loss of the most fertile soils	Extreme rainfall, flash floods and runoff intensify erosion damage
Expansion of intensive agriculture and pressure on marginal lands	Continued depopulation and abandonment of upland rural areas	Increasing aridity and desertification risk in vulnerable regions
Rising global food demand increases pressure on soil resources	Limited resources for large-scale restoration and monitoring	Industrial-urban contamination hotspots add to existing degradation

CONCLUSION

This study confirms that soil degradation is a pervasive and accelerating global and Western Balkans problem, driven primarily by erosion, loss of soil organic carbon, inappropriate agricultural practices, land-use change and intensifying climate stress. While the dominant processes are broadly similar at the global scale and in Montenegro and Serbia, their impacts are particularly severe in fragile mountain-karst and erosion-prone environments with limited reserves of high-quality agricultural land. The ecological consequences include the loss of ecosystem services, reduced fertility and productivity, biodiversity decline and increased hydrological instability. At the same time, socio-economic impacts are expressed through yield and income losses, rural depopulation, rising infrastructure and restoration costs, and heightened vulnerability to climate extremes (JRC, 2024). Comparative and SWOT analyses show that both countries have significant opportunities to reduce degradation through conservation and regenerative agriculture, protection of scarce fertile soils, restoration of abandoned and degraded land, and improved risk-based land-use planning (JRC, 2024). To be effective, these technical measures must be supported by stronger legal and institutional frameworks, systematic monitoring and targeted incentives for sustainable soil management, so that soil resources can continue to support biodiversity, food security and rural development under changing climatic conditions (JRC, 2024).

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HOW VINEYARDS AND WINE PRODUCTION CAN BE PROTECTED FROM FUTURE WILDFIRES IN GREECE

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Abstract: Wildfires in the wider area of southern Rethymno, Crete Island, Greece, have proven to be detrimental to the local economy in many ways, which is mainly based on agricultural and livestock activities. The fire that burned the vineyards around the town of Melampes on July 15, 2022, is such a characteristic and catastrophic fire with negative effects caused by the loss of dozens of hectares of vineyards and olive groves. At the region, we can find the vine varieties of Vidiano, Thrapsathiri, Melisaki, Plytos, Liatiko, Kotsifali, Mavromeikos cultivated in over 60 ha. In this work, we used fire simulation models to understand how and where future fires may start and threaten the vineyards and olive groves of Melampes, with what intensity they are predicted to burn, and from which areas they are most likely to propagate with high fire spread rate. Simulations can also show where measures to reduce fuel or change the composition, structure and arrangement of vegetation will be most effective to mitigate these future fire incidents. This study suggests areas where, based on the fire simulation results, by implementing fuel management or creating new fire breaks (i.e., zones with complete remove of surface and overstory vegetation), can enable the containment or reduction of the intensity and severity of burning. The main goal of this study is to protect the vineyards of Melampes from a new fire and the results to act as an auxiliary and complementary to the future drafting of the Fire Protection Plan of the prefecture of Rethymno. This paper provides a brief history of the study area and analyzes the dominant types of vegetation and surface cover, fuel types (i.e. what are the loads and arrangements of dead and living biomass on the surface available for combustion from a fire) and the expected fire behavior in each of these. A brief description of the evolution and immediate effects of the fire of July 15, 2022, is presented. Regarding materials and methods, the simulation models, inputs and assumptions made to produce the results of the analysis are described. The results are presented with maps that depict important information related to wildfires in the study area. Finally, a discussion follows highlighting the conclusions and proposals regarding the fire protection of the vineyards.

Keywords: Wildfire simulations, Fuel treatments, Crete, Agricultural production, Minimum Travel Time algorithm

INTRODUCTION

The wildfire in the prefecture of Rethymno, near the town of Melampes (Crete Island, Greece) on July 15, 2022, burned a large agricultural area dedicated for olive and grape production, which in turn are used to produced different wine varieties and extra virgin olive oil in cooperative and private facilities of the region. Apart from the direct economic

losses that are obvious and measurable, the fire caused a psychological burden and disappointment to the producers and vinters of the region, which, if not reversed, can cause social problems such as the migration and exodus of young people, in addition to the halting of investments and entrepreneurship of investors. It is therefore imperative to take measures to mitigate the negative socio-economic effects the fire has caused. Even more important is to understand the historical patterns of the region's fires and to predict, as far as possible, how future fires may start and develop into large-scale incidents, threatening crops, settlements and people for one more time.

The difference of southern Rethymno in relation to other fire-affected areas of mainland Greece is that the vegetation is comprised of phryganic ecosystems and grassland instead of forests dominated by pines, and when a fire burns into the area it does not have a strong ecological impact since the species composition has inherent ability to fully recover to its previous state after three to five years. This is positive from an ecological perspective, but extremely negative and worrying for the issues of fire protection, since after a short recovery cycle, the biomass becomes abundant again and can cause a new fire, exactly like the previous (or even worse). This does not occur in coniferous or broadleaf forests, in which the vegetation returns to its previous state after 10-20 years, during which new fires have different characteristics (surface instead of crown), rate of spread (higher compared to the previous state) and moderate spread and intensity (lower than in the past).

The wider area of southern Rethymno is mountainous with steep slopes and rough terrain, which makes it difficult for fire trucks to access and operationally utilize them due to the long transition time from one area to another through narrow roads with many turns, but also the rate of spread that fires can develop there (large slopes increase the speed of fire rate of spread). The vineyards of Melampes are at altitudes between 500 - 900 m above sea level. Regarding slopes, 55% of the study area has slopes up to 12 degrees, 28% of 12-21 degrees, while steep slopes dominate at 12% (21-30 degrees) and 5% (30-45 degrees). The wider area of the vineyards has a north and northeast exposure, which gives more moisture to the area compared to the southern and southwestern exposures facing the Libyan Sea.

The types of land cover, as they were mapped from the combination of Corine 2018 and the results of the First National Forest Census of 1991 are presented in Figure 1. The wider study area has a total area of 40.000 ha. The area is dominated by the Olives with over 10.000 ha, followed by the meadows with sparse woody vegetation (mainly brushwood) with 9.500 ha and the sclerophyllous vegetation which covers 5.000 ha. In total, the vineyards extend to an area of 400 ha, of which 62 ha are in Melampes. The most characteristic fuel types of the study area are presented in Figure 2.

In Crete, grape phylloxera (*Ph. vastatrix* or *vitifolia*) appeared during the 1920's since there was no extensive viticulture and all vineyards were planted in sandy soils. However, when Phylloxera arrived, the Greek state reacted quickly by calling on producers to replant with new tolerant varieties, subsidized at the time, to eradicate the insect. In Heraklion, where there were more intensive cultivations, and historically, it was mentioned that during the Venetian era, there was intense commercial activity both in the transport of grapes, grape "must" and wine from the ports, and large-scale replanting was observed during the period. There, the soils are clay and limestone, so the native varieties such as Sultanina, Tachtas, Kotsifali and Liatiko disappeared. In Rethymno, as the cultivation of vines was mainly

intended for domestic consumption and not commercial, the growers did not pay much attention to replanting, as the soils are intensely sandy and the insect cannot survive there. Today, therefore, Rethymno, along with some areas of Sitia, are the only areas in Crete, and of the few in Greece, where pre-phylloxera vineyards are found.

Specifically, in southern Rethymno, in Melampes, in 1979, 70 ha of self-rooted vineyards were recorded. Unfortunately, today, after the successive fires (14 in total during 1964-2022), only half of them remain. In Fourfouras (Amari), a village at the foot of the mount range Psiloritis, about 10 ha exists, but there is also a strong abandonment of the land, mainly due to overgrazing. Scattered autonomous vineyards can be found in other villages. In an old, preserved vineyard we can find the varieties Vidiano, Thrapsathiri, Melisaki, Plytos, Liatiko, Kotsifali, Mavromeikos and some table varieties and the quota depends on the region. In Melampes and neighboring villages, there are 40 winery partners (growers).

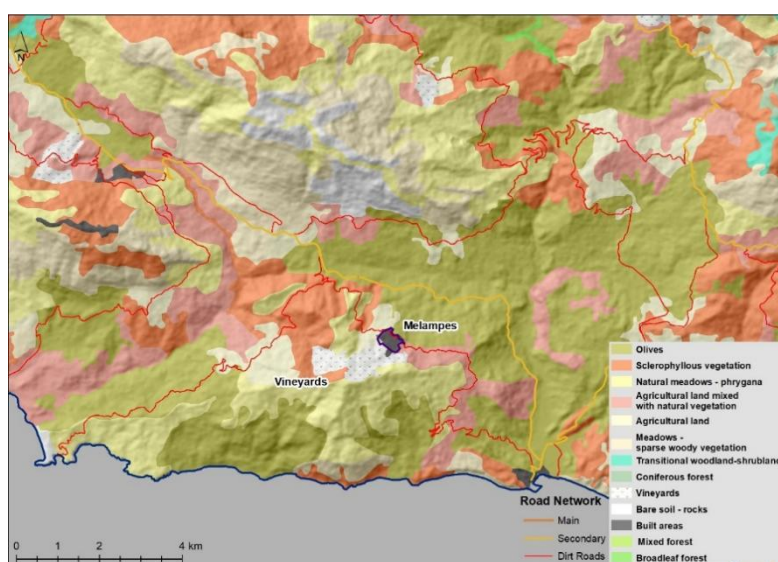


Figure 1. Types of land cover according to Corine 2018 and the First National Forest Census of 1991

In southern Rethymno, the “Iliana Malihin winery” is the only one, and in the entire Prefecture, only six established and certified wineries exist, while in Crete there are 36 in total (more than 40 if we count the uncertified). According to the Greek Statistics Agency, in 2022 the total production of grapes was about 708 thousand tons and in 2023 608 thousand tons, and we know that after 2023 the production has decreased sharply due to climatic conditions, hence the strong price increases in grapes. The vineyards at the neighboring to Melampes village of Saktouria were intensively affected by the 2022 fire, all consumed. In Melampes we know that during the 80s, at the peak of production, about 500 t of grapes were produced. Today, after the fire and the difficult climatic conditions, they harvest an average of around 2000 kg/ha from the old vineyards.

In Southern Rethymno intense drought prevails, and strong winds at sensitive stages of plant development can heavily affect production. The disease of powdery mildew, currently found in the area, is treated with wetting sulfur or dust. In 2023 there was mild powdery mildew effect, but due to the dry winds it only affected the leaves without substantial

reduction of production. The State agricultural policy is not very supportive of the vineyard growers without providing substantial help, deterring young people from working in vineyards. Phylloxera is speculated to still exist, which is why it is mandatory to plant resistant plants. Now the variety “Vidiano” is basically planted due to its popularity but there the varieties Thrapsathiri, Melisaki, Plytos, Liatiko, Kotsifali, Mavromeikos are cultivated. The “Iliana Malihin winery” produce the single-varietal wine Vidiano, another wine with Thrapsathiri, and a third blend wine, i.e. co-vinification of all the varieties.

The fire that burned the vineyards and threatened Melampes started at 10:48 on July 15, 2022. On that day, the official fire danger risk index issued by the General Secretariat for Civil Protection ranked the whole island of Crete in a danger class of 4, i.e. Very High. The duration of the active burning of the fire (i.e., until the final demarcation of the perimeter at its maximum spread) was about a day and a half, i.e. until late afternoon of July 16, 2022. Despite the final demarcation of the perimeter, the fire remained under partial control resulting in flare-ups in the wider area until July 17, 2022, while the final burning in the vineyards of Melampes happened on July 18, 2022.

From information received from nearby weather stations, the dominant direction of wind was the north, while there were periods when the winds turned to northeast and northwest, mostly during the night. The winds were blowing with gusts of up to 85 km/h (9 Beaufort), while at the time of its ignition they ranged between 6 and 8 Beaufort (45-60 km/h). The average wind speed ranged between 12-28 km/h (3-4 Beaufort). The effect of these strong winds, which blew from the aforementioned directions, drove the fire with momentum to the south, reaching as far as the Libyan Sea, overcoming the mountain range above Melampes, burning a total of 2.000 ha according to the official record of the Fire Service (Figure 3).



Figure 2. Characteristic quantity and arrangement of live and dead fuel in fuel model (Scott and Burgan, 2005) GS1 (top-left), GS2 (top-right), SH5 (bottom-left) and GR1 (bottom-right)

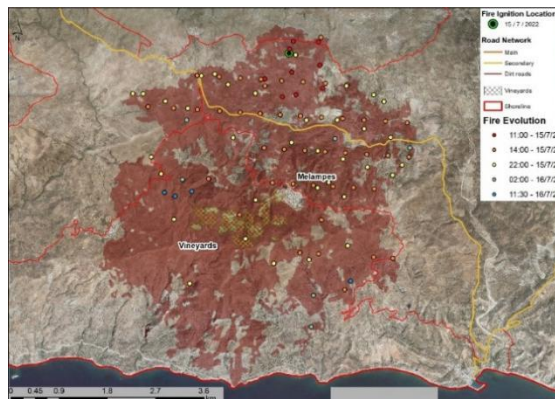


Figure 3. Burned area and evolution of the fire that broke out on the morning of July 15, 2022. The fire burned 2.000 ha and started near a provincial road west of the settlement of Orne

To extinguish the fire, the Hellenic Fire Service used direct methods of suppression, i.e. with extensive use of water both by ground firefighting equipment and with the use of helicopters since due to the strong winds, the firefighting planes were unable to operate in the area. On July 15, 2015, an all-night battle was given, but the fire could not be controlled and continued its southward course the next day. The situation became very difficult because the stormy winds were constantly changing directions, such as at midnight on July 15th where the wind turned from the northwest direction to the northeast. During the first day, 110 firefighters, 33 vehicles and four helicopters participated in the firefighting operation. In total, according to the official data of the Fire Service, 186 firefighters, 44 ground personnel, 10 Army personnel and 36 others (volunteers and residents) participated in the operations. According to the official data of the Fire Service, the burned forested areas amount to 336 ha, the grassland - phrygana areas to 532 ha and the agricultural and livestock areas to 1.118 ha. Satellite image analysis calculated that of the about 2.000 ha affected, olive groves account for 38.5%, natural pastures for 26.7%, sclerophyllous vegetation for 15.6%, agricultural land (crops) for 12.7%, vineyards for 4.9%, and areas with sparse vegetation 1.2%. Using the cadastre data, forest areas make up 16.5%, grassland 7.5% and non-forest areas 76% of the burned area. Finally, of all vineyards in the west Melampes (62 ha), 18% remained unburned and unaffected, i.e. 11 ha (Figure 4).



Figure 4. The main vineyards in Melampes and the footprint of the fire of July 15, 2022 (brick color). The areas within the vineyards that were not affected by the fire and amount to 11 ha are distinguished with light brown color

MATERIAL AND METHODS

For fire behaviour simulations, it is necessary to use data and information describing topography, weather conditions, fuel moisture content and vegetation status. The parameters that are most difficult to model and map concern vegetation and especially the properties of the fuel. Modeling is a complex and time-consuming process that requires a detailed classification through measurements of the various physicochemical properties that characterize it in the field, followed by its quantification through the application of methods and working hypotheses (Keane et al., 2001). As mentioned above, fuel models (FM) mainly provide information about the fuel load in each diameter class, i.e. how "thick" the dead branches are in each area, the dead fuel, but they are also directly related to the percentage of moisture content of each fuel size class.

For forest canopy height, ETH Global Canopy Height, 2020 edition data were used (Lang et al., 2022). Crown cover was derived from Copernicus' Tree Cover Density at a spatial resolution of 10 m and reference year 2018. For canopy base height, we used data from field inventories and local/specific knowledge to assign species-specific fixed values for canopy base height depending on the vegetation species. For the canopy bulk density, we used mapping tables (Table 2 in Keane et al. 2001) that described the available canopy fuel in kilograms per cubic meter for three canopy cover classes (Low: 21-50%; Medium: 51-80%; High 81-100%).

Since the available biomass that can be consumed from a fire in the study area is mainly surface and the trees there came from plantation of orchard trees or are individuals in a sparse arrangement, the fires simulated are in their vast majority surface and the crown data contributed only minimally to the spread and intensity of the fires since there are not dense forest stands there.

The FlamMap software (Finney, 2002, 2006) was designed to extend the application of established fire behavior simulation models at the field level (landscape). All equations and models of calculating fire behavior assume that fuel moisture, wind speed, and direction are constant over time. FlamMap is designed to investigate the spatial variation of fire behavior with calculations performed autonomously for each cell of a gridded. FlamMap requires spatial inputs from GIS for both topography and for the distribution and quantity of fuel in the landscape, which are either required or optional and are coalesced into the software to create a new Landscape file (LCP).

Conducting fire behavior simulations with the MTT algorithm of the FlamMap software offers several advantages. The spread of fire is calculated based on the equation of Rothermel (1972), while the start and spread of the headfires relies on the work of the Van Wagner (1977), combined with Huygens' rule. The MTT algorithm is suitable in cases of parallel data processing and multi-processing analysis, having the advantage that it generates combustion probabilities of the entire analysis area by simulating thousands of possible new outbreaks. This probability is an estimate that a cell will burn from some random ignition among the thousands of ignitions simulated. MTT is looking for the fastest path of fire spread along straight cross-sections, connected by knots (Finney, 2002). The result is the production of a Burn Probability (BP) map that shows which areas are most vulnerable and prone to burn from one or more fire incidents, as well as which are more

"fire-proof". The BP for each cell is an estimate of the probability that this cell will burn from an accidental ignition within the analysis area and with combustion conditions similar to those of historical wildfires in the region. The map values have a BP range from 0 (unburned) to 1 (maximum probability of burning). The Conditional Flame Length (CFL) is the weighted probability of the flame length, considering that the start and behavior of the fire acts as a measure of assessing the risk it causes (Ager et al., 2010).

High probability values are linked to the size of fires that will occur within an area, which means that under the same circumstances, larger fires produce higher burn probability than small fires (each burning a larger part of the area). The MTT does not include the assessment of the absolute risk of future fire occurrence, but it does provide a quantitative framework for the analysis of potential losses from specific fire incidents, while at the same time it is a method for quantifying the effectiveness of fuel management scenarios in the field, calculating the possible spread, intensity and impact of the fire.

The calculations of the Treatment Optimization Model (TOM) are based on the calculations of the Minimum Travel Time (MTT) algorithm to identify the dominant transmission flows of a fire and aims to effectively block them by applying fuel management methods organized in projects with the appropriate dimensions (Finney, 2007). Aiming to assess the impact of prevailing weather conditions, specific areas are sought for the implementation of fuel management projects that will reduce the growth rates of a fire as much as possible for the given intensity of application and extent of the projects (i.e., which methods will be applied and to what extent). The TOM requires an ideal landscape that should describe the proposed implementation of fuel management projects, both surface and crown, in each pixel of the landscape to which management may be applied, and not only in the pixels where they are planned or feasible (e.g. legal constraints) to be implemented. TOM compares the rate of spread (ROS) between the existing and the ideal landscape. The results are rendered in a spatial raster file where each pixel receives values of +1, 0, and -1. The positive sign reflects the areas where the TOM calculated that the rate of spread of the fire decreased after the implementation of the management, the zero those pixels without difference, and the negative sign the areas where the rate of spread of the fire increased after the management.

Initially, it was necessary to determine which wind directions are most often in the area during the months of June, July and August where we have the greatest risk of new fire incidents (all the large fires that affected the vineyards of the area occurred during these three months). Daily data on the prevailing wind direction were collected from nearby weather stations to obtain the frequency of each direction. Almost 40% of all winds blow from the northwest (NW and NNW), followed by the north (N, NNE, NNW) with 27%, the northeast directions with 24% (NE and ENE) and the south directions with 6% (S, SSE, SE, SSW and SW). The humidity conditions defined are very dry for all fuel models (1hr: 3%, 10hr: 4%, 100hr: 5%, LH: 30%, LW: 60%), the wind speed was set at 60 km/h at 10 m above ground with activation of the Wind Ninja model which models the spatial variations in wind speed and direction caused by topography and vegetation, but also the effect of the local winds in the area. The foliage moisture of the crown was set to 100% (120% is an appropriate value for average mid-summer conditions and 100% value for drought conditions), activating Finney's (2004) method with a probability of spotting at 10%. The effect of ground and aerial forest firefighting on any part of the fire perimeter

was not simulated. A total of four simulations were carried out with the same parameters, with the only difference being the front fireline (one north, one northwest, one northeast and one south), setting 335°, 300°, 35° and 180° respectively as the dominant wind direction.

The aim was to assess how fires that can start from different areas in the landscape driven by the wind can affect the vineyards in Melampes, but also where there are opportunities to stop the dominant flows of their spread before they reach the vineyards. We point out that the types of vegetation affected by the 2022 fire have the potential to regenerate rapidly and return to their pre-fire state (structure, composition and biomass loads) between 1-3 years after the fire (with some exceptions such as dense shrubs that require about five years). In southern Rethymno new fires within the burned area after three years will have a behavior (intensity and speed of spread) at least 75% of what happened three years ago - so burning an area does not make it fire-protected and inflammable.

A simulation was carried out with TOM with the fuel conditions prevailing before the 2022 fire. The targeted changes we foresee to be applied should be implemented in all brushlands with fuel models that contain annual vegetation with brushwood (GS1 and GS2) or dense and continuous grassland (GR2 and GR4) converted to low and sparse grassland (GR1).

RESULTS AND DISCUSSION

Stochastic fire simulations with the MTT algorithm showed that about 620 possible fires from a set of 100.000 simulations for the domain of Western Crete can reach Melampes and burn the vineyards, again. Most (580 cases) started within a radius of 5 km from the vineyards, while a few cases burned a very large area, most started even 11 km east of them. This finding, combined with the knowledge we have about the historical fires of the area, demonstrates the spatial mismatch at the level of risk perception and prevention. It is not right to think locally, and it must be understood that the risk can come to the vineyards from fire incidents that are far from the management and prevention capabilities that a community, like Melampes, can implement on its own. Simply put, the future fire that can burn the vineyards again will come from other villages and parts of Rethymno and this requires wider adoption of prevention measures. However, we should not overlook the fact that many of the fires, and those that cause the greatest exposure of vineyards, started near them.

Figure 5 (Left) illustrates the probability of burning, i.e. which locations are most likely to burn a future fire. If, for example, 100 fires are simulated and 10 of them pass and burn from a specific point in the landscape, then this means that the specific cell has a 10% chance of burning. We see that 13 of the 15 vineyards have a high probability of burning (except for 11 and 7), i.e. they are in a high-risk area through which many fires pass and start from many different locations. We note here that the simulations are extended to multiple fire seasons so that we can estimate the effect of different meteorological scenarios and starting points.

Figure 5 (Right) shows the estimated fire intensity expressed in meters (flame length), i.e. how far (not high) the flames reach from the surface. We find that the entire area to the north and northeast of the vineyards has very high flame lengths, exceeding 3 m, which

makes it prohibitive to use personnel and earthmoving machinery for a direct attack on the fire front. It is positive that within the vineyards the flame length is low, and this allows vehicles and ground personnel with fast moving firefighting vehicles to easily suppress the flames if there is sufficient water. If an automatic fire extinguishing system with sprinklers is installed in the area, the results show that it will be sufficient and able to suppress possible future fires (something that would not be possible if the flame lengths were higher). In conclusion, the vineyards of Melampes are at risk of frequent fires which, however, will not burn with great intensity, something that was also recorded by the fire of 2022 when after a few months the vines managed to regrow from the vines without requiring new plantings in most of the vineyards. This would not have happened if the intensity of the fire had been greater and it burned longer inside them.

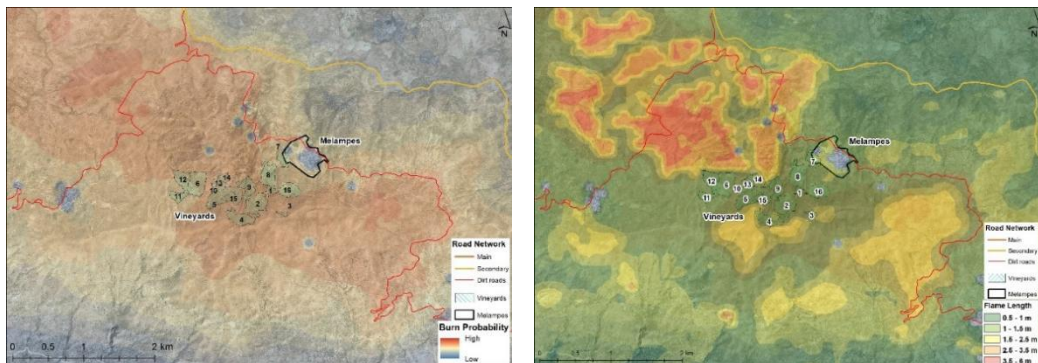


Figure 5. Chances of burning from a large number of simulated fires, with warmer colors indicating a greater probability of exposure by possible future fires (left). Estimated burning intensity (flame length), with warmer colors indicating greater burning intensity from possible future fires (right)

Simulation results of fire spread under extreme conditions show where the major spread flow paths will move faster in the landscape. If it is possible to contain them, then there is a high chance that the fire will not reach the vineyards. Initially, we looked to find at which locations, mainly across the road network, new fire breaks or reduced fuel zones can be opened or widened. These locations intersect the dominant fire flow paths. It is emphasized that a fire break cannot stop a fire on its own and active suppression using water or hand tools from firefighting crews are required to achieve suppression. Figure 6 shows the simulations from four different wind-driven fronts. The proposed fire breaks around the area of Melampes and its vineyards can be seen in bright blue color, in places with a high probability of stopping the dominant flows, placed as a priority across the existing road network. Figure 6 (upper left) shows a potential fire that spreads from a front that started north of the vineyards under the influence of a north wind. It is proposed to construct five new fire breaks with a total length of 2.2 km, two to the north of the vineyards and three to their west-northwest.

Figure 6 (upper right) shows a potential fire that spreads from a northeast front under the influence of a northeast wind. It is proposed to construct four new fire breaks with a total length of 2 km, one to the northeast of the settlement of Melampes, two which will be connected to the settlement of Melampes by extending the zone of fuel removal (the settlement is naturally inflammable or low flammable), and another one in a NNE to SSW direction intersecting the vineyards. Figure 6 (lower left) shows a potential fire that spreads

from a northwest front under the influence of a northwest wind. It is proposed to build four new fire breaks with a total length of 1.3 kilometers, the largest of which will be on the provincial road, two smaller that will extend outside the road network and another one to the west of the vineyards. Finally, Figure 6 (lower right) shows a potential fire that spreads from a southern front under the influence of a south wind. It is proposed to build six new fire breaks with a total length of 1.6 kilometers. One fire zone will be on the saddle between the peaks of Vouvala and Santali, one between southern vineyards, and additional four south of vineyards.

Figure 7 illustrates the extent to which FlamMap's Treatment Optimization Model indicated that it can significantly contribute to reducing the rate of spread of a potential fire if fuel reduction and removal techniques are applied at the center of the study area (pink color). Vineyards have different color gradations, with the warmest colors attributed to vineyards that were estimated to have the greatest exposure to possible future fire incidents (a result of stochastic fire simulations). In total, it is proposed to open or widen new or existing fire breaks with a total length of 7.2 km, and to manage an area of 88.5 ha (pink color). In addition, it is proposed to open a 15-meter deforestation zone with absolute removal of fuel around all the vineyard polygons, the area of which reaches 16.8 ha.

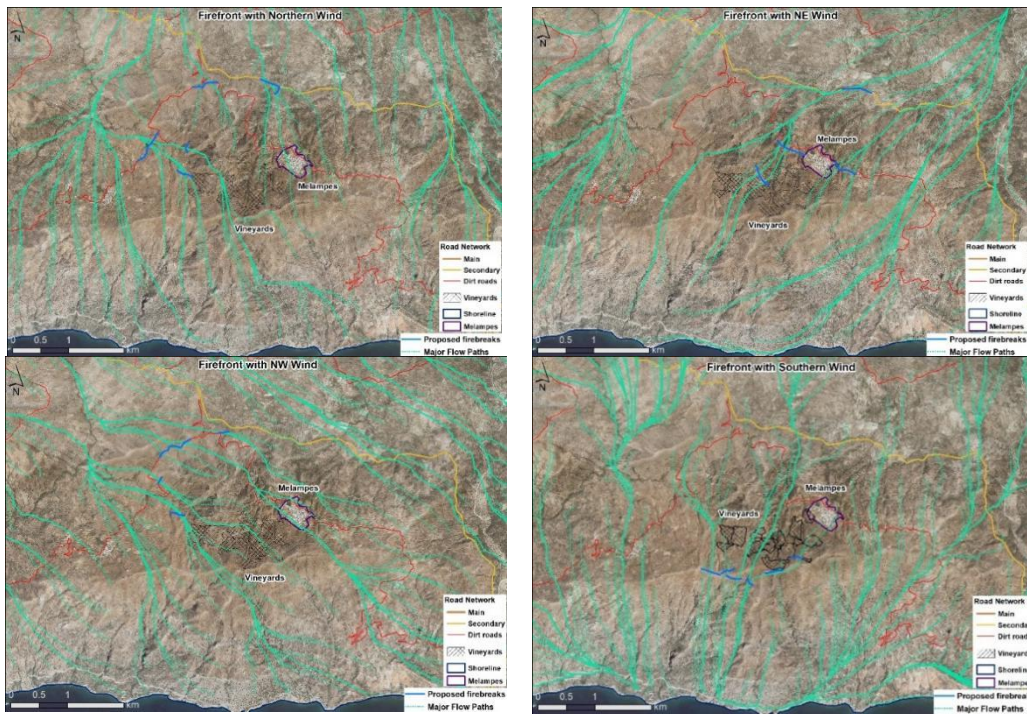


Figure 6. Dominant transmission flow paths (cyan) of a fire that will start from a northern front (top-left), northeast front (top-right), northwest front (bottom-left) and southern front (bottom-right)

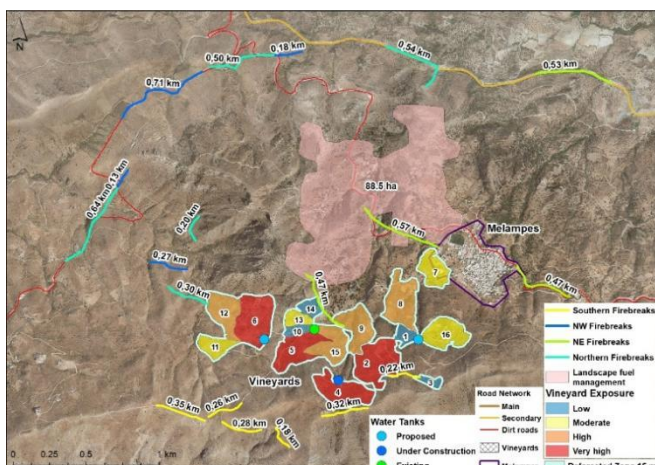


Figure 7. Representation of the proposed fire breaks and fuel removal areas around the vineyards of Melampes. The locations of the two under-construction water tanks are shown in blue, green is an existing one, and cyan are the two proposed

Proposed Measures and Costing

Supply and installation of two plastic water tanks with 25.000 l capacity

Vertical type tank, cylindrical with lid, capacity 25.000 liters, black color, base diameter 3.70 m. The tanks will be made of linear polyethylene resin and will contain antioxidants and UV stabilizers for solar radiation. The material will meet the relevant conditions of the European Union regulations EC 1935/2004 and EU 10/2011. Each tank will have valves for the inlet and exit of water, for drainage, and for overflow. The unit price includes the supply and transport of the water tanks on site and their installation (landscaping, concrete base if required), the valves, spherical isolation switch as well as the connecting micromaterials. Price per unit: 5.000 euros; Total 10.000 euros.

Supply of 4X4 pickup fire trucks with integrated 600 l autonomous pumping system

Supply of a 4X4 vehicle with a removable fire superstructure for the needs of forest protection, prevention and extinguishing of forest fires. The price includes the supply of the fully equipped vehicle, transportation, registration process and other expenses. Price per unit: 55.000 euros.

Fuel removal and pruning in oak forests or olive groves

For the pruning of trees up to 2.5 m from the ground, the removal of the understory, the cleaning of the surface vegetation and the transport of residues by a rented vehicle, the costs are the following:

- Cleaning of understory and surface biomass; Skilled worker per 0.1 ha: €16.85 X 4 hours = €67.36
- Pruning; Logger per 0.1 ha: €21.11 X 2 hours = €42.21

- c) Transport of residues - Stacking; Skilled worker per 0.1 ha: €16.85 X 1 hours = €16.84
 - d) Transport of cleaning residues; Dump truck of 6-ton load per 0.1 ha: €414.8 X 0.2 hours = €82.96
- Price per 0.1 ha: €209.37 X 88.5 ha = €185.292

Fire breaks and construction of reduced fuel zones around the vineyards

In total, it was proposed to open new fire breaks of 7.2 km which, in order to be effective, must be at least 50 m wide (although the 2020 fire management plan specifications provided for this type of vegetation, i.e. brushwood and shrubland, require to be 15 m wide at 70% slopes). Therefore, the total area of fire zones can reach up to 36 ha. To this area, 16.8 ha of reduced fuel zones around the vineyards will be added, i.e. a total of 52.8 ha of fuel removal. For cleaning in broadleaf or brushwood evergreen shrubs and the transport of cleaning residues with a rented vehicle, the costs are the following:

- a) Vegetation clearing; Skilled worker per 0.1 ha: €16.85 X 6 hours = €101.06
 - b) Transport of residues - Stacking; Skilled worker per 0.1 ha: €16.85 X 2 hours = €33.68
 - c) Transport of cleaning materials; Dump truck of 6-ton load: €414.82 X 0.3 hours = €124.45
- Price per 0.1 ha: €259.18 X 52.8 ha = €136.847

CONCLUSION

In summary, this study highlights the need to take the following measures for the protection of the vineyards of Melampes. First, we suggested the creation of new fire breaks 7.2 km long, 50 m wide and with a total area of 36 ha. Second, the creation of fuel reduction zones with complete removal of biomass at a width of 15 m around the vineyard polygons, with a total area of 16.8 ha. Third, the cleaning of the understory and pruning in oak forests and olive groves with a total area of 88.5 ha. Fourth, the supply of two new water tanks of 25 t each and installation near vineyards. Finally, the supply of a 4X4 pickup fire truck with built-in autonomous pumping system and 600 l water capacity.

Figure 8 shows an example of new vineyard plantations in a former forested area dominated by conifers and eucalyptus trees, in northern Portugal in the wider Douro Valley (near Porto). This area burned a decade ago and land was granted to vine farmers so that instead of an extensive deforestation zone without vegetation, new vineyards can be planted there with a goal of having a maintained zone with no dead fuel that will be under the constant care of the farmers, thus, making this zone act as a natural defense zone against possible new future fire incidents. The vineyards of Melampes can perform this role (i.e. the containment of future fires) if enough area can be allocated around them, enabling their expansion, but also to create a zone of complete biomass removal with 15 m width.



Figure 8. Use of vineyards as a reduced fuel zone within a burned area, instead of a deforested fire break in Valo do Douro in Porto (Portugal)

It is easy to understand that the biggest problem with the implementation of the proposed measures is the ownership of the proposed lands to receive fire management measures. This does not mean, of course, expropriations or any change in ownership. The opening of these zones will protect the vineyards, the olive groves and the settlement of Melampes. In addition, it will protect the properties that will accept the implementation of these fire protection measures. The protection and economic development of the region is in everyone's interest. Many of the proposed areas may be either abandoned (e.g. the owners have emigrated), or Municipal / Community / State, or classified as Forested by the Greek Land Registry. These forested areas must be found and prioritized for fuel management and fire protection actions, since there will be fewer social tensions there. We emphasize that the proposed fire protection measures that include the removal of biomass are not permanent since any measure implemented will have a specific life span, between 3-5 years, after which the vegetation will return to its previous state. This requires maintenance of the new fire breaks whenever necessary to maintain their ability to contain future fires. The two new water tanks will fill a gap in firefighting ability for the eastern and western vineyards and can be used both for irrigation (it was proposed to place them at a higher altitude to facilitate the easy natural flow of water), but also for the case of vehicle refueling or even, for the supply of water to automated spraying systems for extinguishing fires if they are installed in the area. Finally, the supply of a new ready-to-act fire truck (i.e. small, flexible and with the ability to carry up to 0.6 t of water) can help with the timely response and suppression of small fire incidents. The vehicle's suppression capabilities will be maximized by utilizing the three new plus one existing water tanks.

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POSSIBILITIES OF USING eDNA TECHNIQUES FOR DETECTING WEEDS AND OTHER PLANTS FROM THE SOIL SEED BANK

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Abstract: Environmental DNA (eDNA) is short DNA fragments left behind by organisms into the nonliving elements of environment and have become a foremost tool of life and environmental sciences to develop models for future, detect current level of ecosystems, get info from past situations since 1980's. The early use of eDNA to detect microorganisms in water, sediment and soil followed by macroorganisms detection in seas and freshwater in the beginning of the 21st century. Today it is possible to detect non-living pollutants in various environments. eDNA barcoding and metabarcoding has opened new horizons. Combining traditional methods or newest ones such as environmental RNA and using apps on site, modelling approach, and new generation sequencing and bioinformatics enabled getting more precise results. eDNA has been used in plant sciences and agriculture but its use in weed science is not common. Introducing eDNA with other related innovations into weed science and invasive alien plants strategies to detect alien introductions and current soil seed bank can make ecological approach more applicable.

Keywords: Weeds, eDNA, Soil seed bank

INTRODUCTION

Humanity faces unprecedented challenges in protecting the environment, sustaining ecosystems, and preserving life amid climate change, biodiversity loss, population growth, and resource exploitation issues largely stemming from the industrialization era. Agriculture both contributes to and suffers from these problems: it must produce sufficient food and resources at affordable costs while ensuring safety for producers and consumers. Consequently, agronomists and farmers should prioritize reducing synthetic agrochemicals, fossil fuel use, soil disturbance, and irrigation, alongside conserving biodiversity. However, weed control has become increasingly reliant on chemicals.

Frequent use of herbicides, especially in developed countries from mid-1990's led to side effects on the environment and non-target organisms, followed by herbicide resistance issues toward 20th century's end. This shift prompted a focus on ecological approaches and integrated weed management (Forcella et al., 1993; Jones and Medd, 2000). Understanding weed seed banks, including seed longevity, has been central to ecological research mainly on annual weeds (Uremiş et al., 2003; Schwartz-Lazaro and Copes, 2019; Šikuljak et al.,

2024; Asav et al., 2025). Seed bank studies extend beyond agricultural weeds to forest weeds, pasture weeds, invasive alien plants, wildlife relationships, and habitat dynamics (Mahé et al., 2021; Warriar and Kunhikannan, 2022; Fabšičová et al., 2024; Kushbokov et al., 2025). Extending seed bank analysis to natural and semi-natural areas reveals methodological challenges, such as time consumption and the need for deep botanical knowledge, necessitating novel methods like environmental DNA (eDNA) (Mahé et al., 2021; Kestel et al., 2022). This review summarizes eDNA applications for detecting weeds and plants across environments and highlights recent advances beyond eDNA.

Brief History of eDNA

eDNA refers to short DNA fragments left behind by organisms into the nonliving elements of environment detectable in soil, air, freshwater, seawater, mud, silt, ice, feces, and permafrost. It comprises DNA from diverse organisms in a given area. However, DNA extracted from isolated microorganisms from environment does not qualify as eDNA (Bohmann et al., 2014).

Although the term "environmental DNA" was first used by Lakay et al. (2007), nucleic acid studies in organic soils date back to 1913 (Ogram, 1988; Banerjee et al., 2022). Early research focused on microbial DNA extraction methods (Catlin, 1956; Torsvik, 1980; Ogram et al., 1987). Detecting *Escherichia coli* in water samples marked as one of the early eDNA applications followed by soil and estuarine studies (Echeverria et al., 1982; Nannipieri et al., 1986; Paul et al., 1988). In the early 1990s, eDNA identified microbes in marine sediments and phytoplankton in saline water, often termed "DNA particles" (Rishan et al., 2023).

DNA-DNA colony hybridization advanced quantification of anabolic and catabolic plasmids, and monitoring of recombinant DNA in environments (Sayler et al., 1985). Detection of aquatic invasive species by using eDNA by Ficetola et al. (2008) was a pioneering work for macroorganism detection (Banerjee et al., 2022). So far, eDNA has been used in many different environments from sea to air, from soil to freshwater to detect macroorganisms for varying aims from species detection to trophic relations, to find out current situation to get information about past, which can be seen in several reviews (Pedersen et al., 2015; Banerjee et al., 2022; Rishan et al., 2023). Species-specific eDNA assays have detected invasive aquatic plants like *Limnobiium laevigatum* (Zhu et al., 2024).

eDNA applications include wildlife forensics, low-density population detection, invasive species monitoring, biodiversity assessment, population dynamics, community structures, ecosystem health, trophic interactions, and historical distributions (Willerslev et al., 2003; Díaz-Ferguson and Moyer, 2014). Beyond these environmental uses of eDNA, it has been used in agriculture sector because agriculture has very large diversity at microorganism and macroorganism levels which many mutualistic and antagonistic species are interconnected with the cultivation of crops and livestock (Kestel et al., 2022). eDNA can be used to identify pests (insects, pathogens other pests), to get information on ecosystem health (soil, microbes and pollinator diversity), and to decide management practices such as fertilizer and pesticide applications (Kestel et al., 2022).

Despite studies on crop pests and diseases, weed research (including environmental weeds) remains limited. Plant eDNA from mud, soil, or sediment approximates seed bank studies, though samples may include remains beyond seeds, organic matter, or extracellular DNA bound to particles (Foucher et al., 2020). Crop DNA persisted up to eight years post-cultivation, peaking in the first three (Yoccoz et al., 2012; Foucher et al., 2020). Grapevine eDNA lingered 65 years post-cultivation, which shows woody plant parts stay longer. Some species (e.g., mustard, rape) are indistinguishable, while dominant weeds like bindweed, knotweed, and ryegrass were prevalent (Foucher et al., 2020). These findings suggest eDNA's potential for weed science: early warning, decision support, herbicide resistance detection so on.

Pros and Cons of eDNA

eDNA's power is evident across life and environmental sciences, yet it is underutilized in agriculture, especially weed science possibly due to protocol gaps or methodological issues. For instance, post-*Cabomba* eradication, eDNA could not distinguish viable from dead plants, indicating persistence years after death (Collins et al., 2022).

Strengths (adapted from Matsushashi, 2016; Kestel et al., 2022; Vasar et al., 2023; Rishan et al., 2024; Martins et al., 2025):

- Detects specific organisms and assemblages in substrates from soil to air.
- Monitors beneficial/harmful organisms in food systems.
- *In silico*, *in vitro*, *in vivo* approaches mitigate limitations.
- Complements traditional methods for improved agricultural monitoring.
- Metabarcoding is simple, cost-effective, sensitive, scalable, avoiding microscopy.
- Minimally destructive (small environmental samples).

Weaknesses (from Banerjee et al., 2022, 2024; Hernández Martínez de la Riva et al., 2025):

- Poor understanding of eDNA ecology/interactions.
- Degradation in environment and false positives/negatives.
- Quantification challenges.
- Lack of standardized protocols (especially for plants), practitioner adoption.
- Need for reference databases, group-specific primers.
- Bioinformatics pipeline improvements.
- High-throughput instrument availability.

Beyond eDNA

DNA barcoding/metabarcoding uses degraded environmental DNA for high-throughput taxa identification via short fragments, enabling large-scale biodiversity studies (Yoccoz et al., 2012; Espinosa Prieto et al., 2023). Universal markers (chloroplast *rbcL*, *trnH-psbA*, *matK*; nuclear ITS etc.) standardize approaches and ITS within the nucleus led to universal barcoding system, which made use of DNA barcoding and metabarcoding (Kress, 2017). Sequencing the chloroplast *trnL* P6 loop from 325 global soil samples advanced vegetation metabarcoding (Vasar et al., 2023). Consistent markers/primers will build libraries for comparable results and ITS within the nucleus led to universal barcoding system, which made use of DNA barcoding and metabarcoding (Espinosa Prieto et al., 2024, 2025).

Not only improving barcoding and metabarcoding methods, but also some other studies have been conducted to use eDNA efficiently. For instance, different PCR methods have been developed to provide rapid precise on-site eDNA detection for fish and suggested to be used in varying taxa and environments including terrestrial ones (Doi et al., 2021; Wei et al., 2024). As mentioned above, eDNA has some drawbacks compared to classical methods as well as viceversa is true as it has been mentioned in the literature related to plant biomonitoring (Banerjee et al., 2022). Coupling eDNA use with classical monitoring methods improved mostly plant biomonitoring as well as other taxa (Johnson et al., 2021; Pont et al., 2022; Martins et al., 2025).

Environmental RNA (eRNA) has gained attraction, building on early microbial RNA work that had focused on microbial RNA and use of RNA in evolution studies (Nannipieri et al., 1986; Olsen et al., 1986; Kagzi et al., 2023). eRNA outperforms eDNA for pollution/ecotoxicology (e.g., microplastics, metals) studies (Greco et al., 2022; Giroux et al., 2023). eRNA suits vertebrates; eDNA, invertebrates although the research question might determine methods selection (Macher et al., 2024). In ponds, eDNA detected higher biodiversity (plants, algae, fungi) than eRNA (Janik-Superson et al., 2025), though results vary (Miyata et al., 2022). Plant eRNA lags other taxa. eRNA degrades faster, originates from living organisms (unlike eDNA from live/dead) (Deiner et al., 2021; Ahi and Schenekar, 2025), but it can be better to detect the recent elements of soil seed bank.

Concluding Remarks

Seed bank analysis is vital for weed management and modeling, but traditional methods are labor-intensive. eDNA offers new avenues for seed bank estimation and weed management. Its use in life/environmental sciences has grown since the 1980s, though bryophytes, pteridophytes, and gymnosperms need more studies (Banerjee et al., 2022). Applications now include pollution assessment, especially estimation of nonliving things. In addition, eDNA techniques have been used in plant science and crop production but not much studies related to weed science and invasive alien plants.

Integrating eDNA with traditional methods and/or eRNA methods improves accuracy. Regional biases (e.g., understudied tropics) must be addressed (Banerjee et al., 2022). Technique/gadget advances are needed (Vasar et al., 2023). Metabarcoding and bioinformatic strategies require focus (Abdelfattah et al., 2018).

Future priorities: global plant eDNA libraries, genomic sequencing, hybrid techniques, big data. Complementary technologies (sequencing, apps, modeling) enable precision, automation, scalability (Clement et al., 2025; Javed et al., 2025).

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CLIMATE CHANGE, BIOLOGICAL INVASIONS AND CHALLENGES FOR SUSTAINABLE CONTROL OF PESTS AND DISEASES IN AGRICULTURAL CROPS

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Abstract: Present-day global agriculture is strongly affected by climate change. Droughts driven by reduced precipitation and higher evapotranspiration directly limit plant growth and yields, while rising temperatures indirectly alter crop cycles and weed communities. Climate change is also expected to intensify pest infestations by enhancing pest reproduction and facilitating biological invasions, whose stages (introduction, colonization, establishment, and spread) are climate dependent. Agroecosystems, due to low biodiversity, are especially vulnerable to biological invasions, increasing the phytosanitary relevance of both invasive and native pests and creating the need to intensify research on control possibilities of their infestations.

Keywords: Global warming, Harmful invasions, Agro-ecosystems, Pest control, Future expectations

INTRODUCTION

Agricultural sustainability is increasingly threatened by the accelerating pace of global environmental change, which is reshaping the functioning and resilience of agroecosystems worldwide. Modern agricultural systems are exposed to a wide range of interacting stressors, among which climate change and biological invasions are particularly significant due to their broad and long-lasting effects on pest and disease dynamics. Climate change modifies key environmental drivers such as temperature regimes, precipitation patterns, and seasonal variability, while also increasing the frequency and intensity of extreme weather events, including droughts, heatwaves, and floods. These changes directly influence the survival, reproduction, and geographic distribution of crop pests and pathogens, often favouring their proliferation and spread (Skendžić et al., 2021). At the same time, the expansion of global trade, human mobility, and landscape modification facilitates the introduction and establishment of invasive species beyond their native ranges. Once established, invasive pests and pathogens can disrupt ecological balances, outcompete native species, and exploit crops that lack effective natural defenses. The combined effects of climate change and biological invasions intensify pest and disease pressures, undermine the effectiveness of conventional control measures, and increase uncertainty for farmers and decision-makers. Addressing these challenges requires the

development of innovative, integrated, and sustainable crop protection strategies that are capable of adapting to rapidly changing environmental conditions while minimizing ecological and socio-economic impacts.

CLIMATE CHANGE AND PEST/DISEASE DYNAMICS

Climate change influences agricultural pests and diseases through a combination of direct effects on the physiology, behaviour, and life history traits of these organisms, as well as indirect effects mediated by host plants, natural enemies, and broader ecosystem processes. Among climatic variables, temperature plays a central role in regulating insect metabolism, development rate, survival, and reproductive success. As temperatures rise, insect life cycles often accelerate, leading to shorter generation times and an increased number of generations per growing season. This phenomenon can result in rapid population growth and higher damage potential in many economically important pest species (Bale et al., 2002; Eickermann et al., 2023). In addition, milder winters associated with climate warming tend to reduce overwintering mortality, enabling pests to persist at higher densities and expand their geographic ranges into regions that were previously climatically unsuitable. Such range expansions have been documented for several major agricultural pests, including the Colorado potato beetle, *Leptinotarsa decemlineata* (Say), as well as numerous aphid species (Deutsch et al., 2018).

Plant pathogens are similarly sensitive to climatic conditions, particularly temperature and moisture. These factors strongly influence fungal and bacterial sporulation, dispersal mechanisms, infection efficiency, and disease progression. Warmer and wetter environments can intensify the incidence and severity of major diseases such as rice blast and wheat rusts (Strange and Scott, 2005). Moreover, alterations in rainfall patterns affect pathogen transmission pathways and soil moisture regimes, often creating favourable conditions for soil-borne and root-infecting diseases (Pautasso et al., 2012). Extreme climatic events, including prolonged droughts and heat waves, further exacerbate these dynamics by imposing physiological stress to plants. Such stress can weaken plant immune responses and defense mechanisms, increasing crop vulnerability to opportunistic pathogens and pest outbreaks. Together, these direct and indirect effects underscore the complex ways in which climate change reshapes pest and disease pressures in agricultural systems.

BIOLOGICAL INVASIONS: DRIVERS AND CONSEQUENCES

Alien species can be defined as “invasive” when they become introduced into areas outside their natural range, where they negatively impact native biodiversity and ecosystem services. Biological invasions are facilitated by human activities including international trade, travel, and landscape disturbance. Invasive species often exhibit high reproductive rates, broad environmental tolerance, and the ability to exploit novel niches (Lockwood et al., 2013). In agricultural contexts, invasive insects, mites, nematodes, and pathogens can rapidly become dominant pests especially because their native natural enemies may be absent or ineffective.

Examples of impactful invasions for the EPPO area may include the spotted wing drosophila (*Drosophila suzukii* Matsumura), which infests soft fruits across temperate

regions (Cini et al., 2012; Sario et al., 2024), and the fall armyworm [*Spodoptera frugiperda* (Smith)], which has recently spread from the Americas to Africa and Asia, causing significant maize yield losses, and is presently representing a quarantine risk for many crops in south European countries (Goergen et al., 2016). Similarly, the bacterial pathogen *Xylella fastidiosa* Wells et al. has decimated olive groves in the Mediterranean, showing how invasive microbes can transform agricultural landscapes and economies (Bucci, 2018).

Invasions can also interact with climate change. All phases of a biological invasion (e.g.: introduction, colonization, establishment, and spread) are influenced by climate change, which facilitates the spread of many alien species and creates new opportunities for them to become invasive, but also reduces the resilience of habitats to biological invasions, with the agroecosystems being particularly vulnerable due to their low diversity. Climatic suitability models suggest that many invasive species will expand their potential ranges under future climates, exposing new crops and regions to invasion risk (Early et al., 2016). Climate-driven phenological shifts may synchronize invasive herbivore activity with vulnerable crop stages, amplifying damage potential.

INTERACTION BETWEEN CLIMATE CHANGE AND BIOLOGICAL INVASIONS

The interplay between climate change and biological invasions presents complex and often synergistic challenges for agricultural and natural ecosystems. Climate change can weaken ecological resistance to invasions by altering competitive interactions, disrupting mutualistic networks, and modifying the availability of critical resources. For instance, drought stress or prolonged heat events may reduce the vigour of native plant species, creating ecological niches that can be rapidly exploited by invasive weeds. These invaders often possess traits that allow them to outcompete crops and native vegetation for water, nutrients, and light, thereby intensifying their negative impacts on agroecosystem productivity and stability. At the same time, climate change can enhance the reproductive success, survival, and dispersal capacity of invasive pest species. Rising atmospheric CO₂ concentrations, for example, may increase overall plant biomass while simultaneously altering leaf chemistry, reducing plant defenses, and creating more favorable conditions for herbivores and other pests (Robinson et al., 2012). When coupled with warmer temperatures, these changes can facilitate the establishment and expansion of invasive pest populations into higher latitudes and previously unsuitable regions. Within agricultural systems, such interactions often contribute to the emergence of pest complexes, in which multiple pest species co-occur and inflict simultaneous damage to crops, significantly complicating pest management strategies. Furthermore, shifting climate patterns can promote the spread of novel disease vectors or expand the ranges of already established ones, heightening the risk of outbreaks. Examples include the changing distribution of virus-transmitting whiteflies, which are becoming more prevalent in regions experiencing warmer conditions, posing additional threats to global food security (Aregbesola et al., 2019; Milenovic et al., 2023a). Understanding and mitigating these intertwined effects are therefore critical for developing resilient, adaptive, and sustainable approaches to crop protection in the face of ongoing environmental change.

CHALLENGES FOR SUSTAINABLE CONTROL

Achieving sustainable control of pests and diseases in the context of climate change and increasing pressures from biological invasions requires a multifaceted approach that addresses interconnected challenges. Solutions must integrate ecological understanding, innovative technological tools, and socio-economic considerations, ensuring that management strategies are resilient, adaptable, and effective across diverse agricultural systems while minimizing negative impacts on ecosystems and communities.

Limitations to Conventional Strategies

Traditional pest control strategies have historically depended heavily on chemical pesticides, particularly within monocultural crop systems. While initially effective, the repeated and widespread use of chemical control has often led to the evolution of resistance among pest populations, creating a major challenge for maintaining long-term pest management effectiveness (Vorley and Dittrich, 1994). This problem is further compounded under climate change, which can reduce pesticide efficacy by increasing pest metabolic rates, accelerating development, and altering feeding or reproductive behaviours, thereby diminishing the intended impact of chemical applications. Invasive pest species add an additional layer of complexity, as they often lack co-evolved susceptibilities to pesticides designed for native or regionally established pests. Their novel interactions with local crops and ecosystems can render conventional chemical programs less effective, requiring higher doses or more frequent applications, which in turn can exacerbate resistance development and environmental impacts. Together, these factors highlight the urgent need for integrated, adaptive, and ecologically informed pest management strategies that move beyond sole reliance on chemical controls while addressing the dynamic pressures posed by climate change and biological invasions.

Monitoring and Early Detection

The rapid detection and monitoring of invasive species, as well as shifting pest populations, is essential for effective and timely management. Early identification allows interventions before populations become firmly established, reducing both ecological damage and economic costs. However, existing surveillance networks are often fragmented and poorly coordinated across local, regional, and international scales, limiting their effectiveness. Delays in detection can allow invasive species to spread widely, making containment and control significantly more difficult and expensive. Climate variability further complicates monitoring efforts, as changes in temperature, rainfall, and seasonal patterns introduce unpredictability into pest life cycles and phenology. This uncertainty can disrupt established monitoring schedules and reduce the accuracy of risk forecasts, making it harder to anticipate outbreaks and allocate management resources efficiently. Improving coordination, integrating predictive modelling and expanding adaptive surveillance strategies, are therefore critical for enhancing the resilience of agricultural systems in the face of evolving pest threats.

Forecasting Under Uncertainty

Predictive models play a central role in risk assessment and in designing effective management strategies for agricultural pests and diseases. However, accurately forecasting pest and disease dynamics under changing climatic conditions remains highly challenging due to substantial uncertainties. Climate projections differ across emission scenarios, and the responses of pests, pathogens, and crops are shaped by complex, multifactorial interactions, including temperature, precipitation, extreme events, and biotic interactions. These uncertainties complicate decision-making and can limit the usefulness of single-factor models. To improve reliability, there is a clear need for integrated modelling approaches that combine climate projections with crop phenology, pest and pathogen biology and landscape-level structure and connectivity. Such comprehensive models can generate more actionable forecasts, guide timely interventions, and support adaptive management strategies capable of responding to dynamic environmental conditions and emerging pest threats (Garrett et al., 2011; Lamichhane et al., 2015).

Sustainable Alternatives and Integrated Approaches

To address these challenges, sustainable pest management must transition toward integrated and resilient strategies, with special emphasis on Integrated Pest Management (IPM) techniques, which combine biological control, host plant resistance, cultural practices, physical methods and a judicious use of pesticides to reduce pest impacts while minimizing environmental harm. Biological control agents, such as parasitoids, predators and entomopathogenic micro-organisms, can provide long-term suppression of pest populations when properly preserved and deployed (van Lenteren, 2012). Naturally, appropriate adaptations to modified environmental conditions resulting from climate change will have to be foreseen and planned, as suggested for example in recent studies on the prospects for biological control of the sweetpotato whitefly, *Bemisia tabaci* (Gennadius), under climate change scenarios (Milenovic et al., 2023b, 2023c). Crop diversification, rotations, and habitat management can also enhance natural enemy communities and disrupt pest life cycles.

Breeding crops for climate-resilient resistance to pests and pathogens is another key strategy. Advances in genomics and phenotyping accelerate the development of resistant cultivars tailored to anticipated climatic stressors (Poland et al., 2011). However, resistant varieties must be part of diversified systems to delay resistance breakdown.

Technological innovations including remote sensing, machine learning, and decision support systems can improve monitoring and targeted interventions. These tools can assimilate large datasets from environmental sensors and pest traps to inform dynamic management recommendations.

POLICY AND INSTITUTIONAL DIMENSIONS

Effective governance frameworks are essential to support sustainable pest and disease control under conditions of global environmental change. Policymakers play a key role in strengthening international cooperation on biosecurity, harmonizing quarantine regulations and investing in efficient monitoring and early-warning surveillance systems. In parallel,

economic incentives that promote the adoption of sustainable agricultural practices, such as payments for ecosystem services, targeted subsidies, and long-term support for extension and advisory programs, can significantly accelerate farmer uptake of resilient pest management strategies. Strengthening linkages between research institutions, extension services, and stakeholders is also crucial to ensure that scientific knowledge and technological innovations are effectively translated into field-level applications. Furthermore, participatory approaches that actively involve farmers and local actors in the co-design and implementation of management strategies can enhance their relevance, feasibility, and long-term adoption, ultimately improving the resilience and sustainability of agroecosystems.

CONCLUSION

Climate change and biological invasions act synergistically to intensify the challenges associated with the control of pests and diseases in agricultural crops. Their combined effects modify pest and pathogen population dynamics, disrupt ecological interactions, and reduce the stability and resilience of agroecosystems. As a consequence, many conventional control strategies, largely based on chemical inputs or simplified production systems, are becoming less effective and increasingly unsustainable. Addressing these complex and evolving challenges requires the adoption of integrated, adaptive, and environmentally sustainable management approaches, grounded in a solid scientific understanding of ecological processes and climate-pest interactions. Such approaches must be supported by responsive and forward-looking policy frameworks capable of promoting innovation, risk prevention, and long-term resilience. Only through coordinated efforts across disciplines, sectors, and spatial scales, linking research, policy, and agricultural practice, can cropping systems remain productive, resilient, and capable of ensuring food security under conditions of ongoing climate change and increasing biological invasion pressures.

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UTILIZING FROM MODERN TOOLS IN PLANT BREEDING

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Abstract: Recent advances in biotechnology and genetic engineering have revolutionized plant breeding through tools like genomic selection, CRISPR/Cas9, high-throughput phenotyping, and molecular markers. These technologies boost precision, efficiency, and resilience in crop development, creating superior varieties with higher seed yield and quality, plus better adaptation to biotic and abiotic stresses. Genome editing tools, in particular, speed up and sharpen breeding processes, while artificial intelligence and bioinformatics handling massive datasets to guide smarter decisions-promise to drive plant breeding forward, especially against devastating abiotic challenges.

Keywords: Sunflowers, Cut flowers, Wild species

INTRODUCTION

The world population is expected to reach 10 billion by 2050. Despite steady increases in food production, climate change bringing drought, floods, extreme temperatures, and new pests/diseases threatens global food security. Developing stress-resistant crop varieties through plant breeding has become essential to ensure sustainable agriculture (Asghar et al., 2025). Traditional breeding methods have fed humanity for millennia but are slow, weather-dependent, and limited by genetic diversity. Modern molecular tools genomics, bioinformatics, and engineering enable deeper genome manipulation, making breeding faster, more precise, and better at combining desired traits while removing undesirable ones (Kaya and Beşer, 2020a, b). To tackle complex abiotic stresses (controlled by many genes and GxE interactions), these tools integrate genomic selection, speed breeding, and high-throughput phenotyping. They accelerate elite germplasm screening and shorten breeding cycles, optimizing quantitative traits to close yield gaps and secure global food production (Çeran et al., 2024).

MODERN TECHNIQUES IN PLANT BREEDING

Genomic Approaches and Molecular Markers

Genomic approaches have accelerated the time-consuming, labor-intensive processes of traditional plant breeding by directly targeting genetic variation in plant genomes. Their foundation lies in molecular markers that detect DNA differences (Kaya and Beşer, 2020b).

Molecular Markers and Marker-Assisted Selection (MAS)

Molecular markers are specific DNA sequences in the plant genome that reveal genetic variation. Various types including Restriction Fragment Length Polymorphism (RFLP), Simple Sequence Repeats (SSR), and Single Nucleotide Polymorphisms (SNP) support applications like genetic mapping, variety identification, and diversity assessment. SNPs stand out today due to their abundance across genomes and compatibility with high-throughput genotyping platforms (Collard and Mackill, 2008).

Marker-assisted selection (MAS) uses these markers to identify desirable traits (e.g., disease resistance, yield, quality) early in breeding populations. It excels where phenotypic selection proves challenging or slow such as detecting resistance genes without field exposure shortening cycles, boosting efficiency, and proving especially valuable for oligogenic traits and heterozygosity management (Varshney et al., 2021).

Genomic Selection (GS)

Unlike marker-assisted selection, genomic selection (GS) predicts the genetic value of quantitative traits using all molecular markers (typically SNPs) across the plant genome (Meuwissen et al., 2001). GS builds prediction models from genotypic and phenotypic data in training populations, then estimates breeding values for candidate plants using only their genotypes to select superior lines (Crossa et al., 2017). This approach dramatically shortens breeding cycles and accelerates genetic gains, especially for traits where phenotyping proves costly or complex. GS success hinges on high-density marker data, accurate phenotyping, and sophisticated statistical models (Van Eeuwijk et al., 2019). Its effectiveness is proven for complex traits like yield, disease resistance, and quality in key crops such as maize, wheat, and soybeans.

Genome Editing Technologies

Genome editing technologies represent revolutionary tools that enable precise genetic modifications in plant breeding. They allow targeted insertion, deletion, or replacement of genes by creating specific cuts in the plant genome, offering unprecedented accuracy and speed compared to conventional methods (Doudna and Charpentier, 2014; Naqvi et al., 2022).

CRISPR/Cas9 System

The CRISPR/Cas9 system derived from bacterial immune defense ranks as the most widely used and powerful genome editing tool. It combines guide RNA (gRNA) that targets specific DNA sequences with the Cas9 enzyme, which cuts the DNA at that precise location. Cellular repair mechanisms (NHEJ or HDR) then introduce desired changes like gene knockout, insertion, or replacement (Kaya and Beşer, 2020b). Key advantages include high specificity, efficiency, simplicity, and low cost, making it ideal for plant breeding applications.

CRISPR/Cas9 applications in plant breeding:

- *Disease resistance*: Editing susceptibility genes or boosting resistance pathways (e.g., bacterial blight resistance in rice) (Wang et al., 2016),
- *Yield enhancement*: Optimizing photosynthesis, nutrient uptake, or flowering genes,
- *Nutritional improvement*: Boosting vitamins, minerals, or proteins (e.g., iron/zinc-enriched rice),
- *Stress tolerance*: Targeting drought, salinity, heat, or cold response genes (Asghar et al., 2025),
- *Herbicide resistance*: Enabling precise weed control without crop damage.

Other Genome Editing Techniques

Before CRISPR/Cas9, techniques like Zinc Finger Nucleases (ZFNs) and Transcription Activator-Like Effector Nucleases (TALENs) enabled targeted DNA cuts for genetic modification. However, their complex design, higher costs, and lower throughput have made them less popular compared to CRISPR/Cas9's simplicity and flexibility, positioning the latter as the dominant tool in modern plant breeding (Gaj et al., 2013; Kaya and Beşer, 2020 a,b).

High-Capacity Phenotyping (HTP)

Accurate phenotyping linking genotypes to observable traits drives genetic progress in plant breeding, but traditional methods are slow, labor-intensive, and subjective, creating bottlenecks in large populations. High-throughput phenotyping (HTP) overcomes this through automated, non-destructive technologies that measure plant morphology, physiology, and biochemistry at scale (Kaya and Beşer, 2020 a,b).

Key HTP platforms:

- **Drones/UAVs**: Multispectral/thermal imaging monitors field-wide health, water stress, and yield potential (Araus and Cairns, 2014),
- **Ground robots**: Track growth dynamics, chlorophyll, and leaf area in real-time,
- **Sensors**: LiDAR, fluorescence, and RGB capture structural/physiological data,
- **AI analytics**: Process massive image datasets to reveal genotype-phenotype patterns (Chen, 2024).

HTP supercharges genomic selection by delivering precise, high-volume phenotypic data, accelerating breeding cycles and enabling rapid development of superior stress-tolerant varieties.

Speed Breeding

Speed breeding (SB) is an innovative technique that dramatically shortens plant breeding cycles, accelerating the time required to develop and market new varieties. Traditional breeding often depends on seasonal conditions, taking months or years per generation. SB overcomes this by optimizing environmental controls to rapidly advance plant growth (Ćeran et al., 2024).

The core principle involves providing ideal light, temperature, humidity, and nutrients to compress growth cycles. Key components include:

- *Extended photoperiod*: Artificial lighting for 16-22 hours daily speeds vegetative growth and triggers early flowering,
- *Optimized temperature and humidity*: Species-specific conditions maximize growth rates,
- *Intensive nutrient management*: Continuous feeding supports accelerated development.

This approach enables 4-6 generations per year in crops like wheat, barley, rice, and canola doubling or tripling traditional rates and dramatically accelerating genetic progress.

SB reaches maximum potential when combined with modern tools like genomic selection (GS) and CRISPR/Cas9. GS-identified superior genotypes can be rapidly multiplied through SB, while CRISPR-edited plants quickly advance to stable field-ready lines. These integrated strategies form the foundation of next-generation plant breeding, particularly for addressing urgent climate adaptation needs (Jaganathan et al., 2020).

Artificial Intelligence and Bioinformatics

Modern plant breeding generates vast, complex datasets from genomics, transcriptomics, proteomics, metabolomics, and phenomics. Integrating and analyzing these diverse data sources reveals insights unattainable through traditional methods alone. Artificial intelligence (AI) and bioinformatics tools play a pivotal role in enhancing the efficiency and accuracy of breeding programs by processing massive datasets, identifying patterns, and supporting data-driven decisions (Singh and Singh, 2020).

Machine learning (ML) algorithms play a central role in modern plant breeding, particularly in developing genomic selection models and predicting phenotypic traits. Algorithms such as Support Vector Machines (SVM), Random Forests, and Deep Learning enable breeders to model complex genotype-phenotype relationships more accurately, leading to better-informed genotype selection decisions (Singh and Singh, 2020).

For instance, ML models frequently outperform traditional statistical methods when predicting complex traits like yield and disease resistance from high-dimensional genomic data, providing breeders with powerful tools for precision selection in large populations.

Integration of Multiple Omics Data

Bioinformatics provides computational tools and algorithms for storing, managing, and analyzing data across different omics layers (genomics, transcriptomics, proteomics, metabolomics). Integrating these datasets offers a comprehensive understanding of complex biological processes, such as plant growth, development, and stress responses. By combining multi-omics data, AI algorithms can identify novel gene candidates, map gene regulatory networks, and propose targeted breeding strategies (Ma et al., 2020; Naqvi et al., 2025). Together, AI and bioinformatics enable data-driven decision-making in plant breeding, accelerating program efficiency and effectiveness while supporting more sustainable agricultural systems.

Discussion and Future Perspectives

Integrating modern tools into plant breeding holds tremendous potential for achieving global food security and sustainable agriculture but cost and accessibility remain barriers for small-scale programs (Kaya and Beşer, 2020a). Furthermore, legal regulations regarding CRISPR-edited plants vary significantly between countries, impacting commercialization (Bortesi and Fischer, 2015). However, several challenges must be addressed to make these technologies widely accessible and fully effective. In specific crops like sunflowers, utilizing wild species remains a primary genetic resource for introducing diversity and resistance (Jocić et al., 2015; Kaya and Vasilevska-Ivanova, 2021). The transition from traditional to modern "Alien Gene Transfer" is essential for future crop improvement (Kaya, 2014).

Cost and Accessibility

Advanced genomic tools like sequencing, high-throughput phenotyping, and genome editing demand substantial investments, creating barriers for small-scale breeding programs in developing countries. Lowering costs and enhancing accessibility are essential to maximize their global impact. International collaborations and public-private partnerships can help bridge this gap (Kaya and Beşer, 2020a,b).

Legal Regulations and Ethical Debates

Genome editing technologies, particularly CRISPR/Cas9, raise legal and ethical debates due to their ability to precisely alter plant genetics. The distinction between Genetically Modified Organisms (GMOs) and genome-edited plants is still unclear in many countries. While some countries regulate genome-edited plants similarly to traditional breeding products, others subject them to GMO legislation. These legal uncertainties can slow the development and commercialization of new varieties. Public perception and acceptance of these technologies is also a significant factor. Transparent communication and scientifically based information are essential to gaining public trust (Kaya and Beşer, 2020b).

Integrated Breeding Strategies

Modern tools achieve maximum impact through integrated breeding strategies that combine genomic selection, high-throughput phenotyping, genome editing, and speed breeding. For instance, HTP data enhances GS models, while CRISPR edits can be validated in rapid cycles. This synergy boosts efficiency, accelerates timelines, and improves predictability in breeding programs (Kaya and Beşer, 2020b).

OVERVIEW OF MODERN TOOLS

Modern breeding tools genomic selection, CRISPR/Cas9 editing, high-throughput phenotyping, and molecular markers transform traditional methods into precise, efficient processes for developing superior plant varieties.

1. **Genomic Selection:** Genomic selection shortens breeding cycles by predicting genetic potential early using DNA data combined with phenotypes. This approach revolutionizes selection accuracy and speed.
2. **CRISPR/Cas9 Technology:** CRISPR/Cas9 enables precise trait edits but faces regulatory and public acceptance issues. These challenges must be navigated for widespread adoption.
3. **High-Throughput Phenotyping:** Robotics and imaging deliver real-time trait data, revealing plant stress responses. Such insights speed up resilient crop development (Araus and Cairns, (2014).
4. **Molecular Markers:** Markers streamline trait mapping and selection, accelerating beneficial gene integration into commercial varieties.

Strengths

A key strength of the review lies in its interdisciplinary lens, blending genetics, technology, and environmental sciences for a comprehensive take on modern plant breeding. It backs a wide array of tools with up-to-date research, boosting credibility and timeliness. The researchers thoughtfully weigh each technology's pros, cons, and ethical angles (Watson et al., 2018).

Limitations

Despite its strengths, the review has limitations. It covers technical aspects well but lacks case studies showing real-world applications and results. A deeper dive into economic impacts and accessibility for smallholder farmers would better contextualize modern plant breeding's socio-economic realities (Kaya and Beşer, 2020a).

Future Directions

To boost modern tools' role in plant breeding, the authors recommend key future research paths. Integrating artificial intelligence into breeding workflows shows strong potential for gains. Strategies must also prioritize accessibility for diverse stakeholders, especially small farmers in developing areas, to drive equitable advancement (Naqvi et al., 2022).

CONCLUSION

Plant breeding remains crucial for global food security and climate resilience. Traditional methods laid strong foundations, but modern tools like genomic selection, CRISPR/Cas9 editing, high-throughput phenotyping, and speed breeding have revolutionized the field with unprecedented speed, precision, and efficiency. Artificial intelligence and bioinformatics further empower data-driven decisions, unlocking resilient, nutrient-dense crops at scale. Integrated application of these technologies promises to outpace evolving challenges, delivering disease-resistant, stress-tolerant varieties essential for sustainable agriculture. Despite costs, regulations, and ethical hurdles, their transformative potential is undeniable, driving breakthroughs to feed future generations. Future research must prioritize cost reductions, global accessibility, and real-world validation, especially for smallholder farmers. The review "Utilizing Modern Tools in Plant Breeding" excels in dissecting these innovations, balancing technical depth with broader implications, though

it could expand on case studies and socio-economics. By illuminating pathways forward, it strengthens the case for accelerated, equitable adoption worldwide.

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HERBICIDE TOLERANT PLANT BREEDING IN CEREALS

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Abstract: The breeding of herbicide-tolerant crop plants dates back to the 1980s. To develop herbicide-tolerant varieties, tolerance genes are obtained from naturally occurring gene sources, from material obtained through mutation, or through interspecies gene transfers using biotechnological methods to create genetically modified organisms (GMOs). Most of the imidazolinone-tolerant plants have been improved with conventional plant breeding methods. Imidazolinone herbicides can control weeds, including those closely related to the crop itself and some key parasitic weeds. Imidazolinone-tolerant crop production has benefits of controlling weeds, including those closely related to the crop itself and some key parasitic weeds. There are imidazolinone-tolerant varieties has been improved in corn, rice, canola, sunflower, wheat, barley, lentil, chickpea and sorghum.

Keywords: Cereals, Imidazolinone, Tolerance

INTRODUCTION

Weeds can be controlled either by herbicides or mechanically. Although chemical control is a cheaper and more effective method, it is not always possible to develop selective or broad-spectrum herbicides for every crop. Developing plants resistant to broad-spectrum herbicides to control weeds, and cultivating these crops while using broad-spectrum herbicides, offers advantages to growers. The breeding of herbicide-tolerant crop plants dates back to the 1980s. To develop herbicide-tolerant varieties, tolerance genes are obtained from naturally occurring gene sources, from material obtained through mutation, or through interspecies gene transfers using biotechnological methods to create genetically modified organisms (GMOs). Except for GMOs, the other two methods are classical breeding techniques, and it is easier for plant varieties developed through these methods to enter production. Varieties developed through GMOs are strictly regulated in many countries and are even banned for cultivation in some countries. The cultivation area of herbicide-resistant GMO plants covers 47% of the total transgenic production area worldwide (Prakash et al., 2020). The cultivation areas for herbicide-resistant plants such as corn, sunflower, rice, canola, etc., obtained through classical breeding methods, have vast area.

Broad-spectrum imidazolinone herbicides, which include imazapyr, imazapic, imazethapyr, imazamox, imazamethabenz, and imazaquin, control weeds by inhibiting the enzyme acetohydroxyacid synthase (AHAS), also called acetolactate synthase (ALS).

AHAS is a critical enzyme for the biosynthesis of branched-chain amino acids in plants (Tan et al., 2005). The imidazolinone herbicide group, a broad-spectrum herbicide, controls grasses (jointed goatgrass, feral rye, *Bromus* species, Italian ryegrass, wild oats, and volunteer cereals) and some spring and winter annual broadleaf weeds (shepherd's purse, henbit, field pennycress, chickweed, and mustard species) (Johnson et al., 2023).

Imidazolinone herbicides can control weeds, including those closely related to the crop itself and some key parasitic weeds. A single target-site mutation in the AHAS gene may confer tolerance to AHAS-inhibiting herbicides, making it technically possible to develop the imidazolinone-tolerance trait in many crops (Tan et al., 2005).

Imidazolinone herbicides are very broad spectrum of weeds and low toxicity to animals, birds, fish, invertebrates (Shaner, 2003). Since animals do not synthesize all the amino acids they require and obtain some from plants or bacteria, imidazolinones tend to be less toxic to animals compared to herbicides with other modes of action (Reade and Cobb, 2002). Due to all these characteristics, imidazolinones, belonging to the ALS inhibitor herbicide group, have been prioritized for the development of herbicide-tolerant plants.

Imidazolinone-tolerant Corn

The first imidazolinone-tolerant plant developed is corn. The development of imidazolinone-tolerant corn began in 1982. In tissue culture studies, selection with the imidazolinone herbicide imazaquin from callus resulted in the development of imidazolinone-tolerant corn lines XA17, XI12, QJ22, XS40, ZA54, UV18, AC17, and QT15 from the A188 × B73 hybrid (Shaner et al., 1996; Newhouse et al., 1991). From these mutants, XA17 and XI12 lines were introduced into commercial corn varieties and started being marketed in 1992 as IMI corn. This imidazolinone-tolerant plant production later was called Clearfield® system. Several imidazolinone-tolerant maize lines, including mutant 1 and mutant 2, were also successfully obtained by using the chemical mutagen ethyl methanesulfonate (EMS) to mutagenize pollen from the inbred maize line UE95. Imidazolinone-tolerant maize from this source was subsequently commercialized (Shaner et al., 1996; Bernasconi et al., 1995). Imidazolinone-tolerant corn hybrids are 1000 times more tolerant to imazethapyr and imazapic compared to standard corn hybrids (Newhouse et al., 1990).

The use of IMI-tolerant corn seeds in Clearfield® production in the USA in 2002 was approximately 4.9 million hectares, yet this constituted only 15% of the total corn cultivation area (Tan et al., 2005).

Imidazolinone-tolerant Oilseed rape

Imidazolinone-tolerant oilseed rape was improved with mutation of microspores of the oilseed rape variety Topas with ethyl nitrosourea (Swanson et al., 1989). Five double-haploids survived soil treatment with imazethapyr, and two of the lines showed superior tolerance to imazethapyr. The two most tolerant mutants were P1 and P2, also referred to as PM1 and PM2 (Shaner et al., 1996; Swanson et al., 1989). Later imidazolinone-tolerant oilseed rape varieties were developed with crossing PM1 and PM2 mutants and were first

marketed as Smart canola in 1995. Later it was called and marketed as Clearfield® canola (Tan et al., 2005).

Canola Clearfield® cultivation system production area was reached 4-4.9 million hectares, accounting for 20% of the total canola production area in Canada in 2000-2001 (Simard et al., 2002).

Imidazolinone-tolerant Rice

Imidazolinone-tolerant rice was improved with mutation breeding. EMS was used to obtain imidazolinone-tolerant rice from seeds, the rice variety AS3510. To select imidazolinone-tolerant rice plant, M₂ plants were sprayed with imazethapyr. A single plant was survived from imazethapyr application (Croughan, 1998). This mutant line was called as 93AS3510, and later, imidazolinone-tolerant rice varieties, CL121 and CL141, were developed with making cross with this imazethapyr tolerant material. Imidazolinone-tolerant rice varieties, CL121 and CL141 first marketed in the USA in 2001 (Croughan, 2003; Gealy et al., 2003). Cypress variety seeds were also used to obtain imidazolinone-tolerant rice. Cypress variety seeds were mutagenized with EMS, later M₂ plants of these seeds were foliar treated with imazapyr or imazapic. Twelve plants survived from the application of imazapyr or imazapic treatment and were confirmed to have tolerance. The seven most tolerant lines from these, were selected for further characterization (Croughan, 2002). Subsequently, two imidazolinone-tolerant rice varieties, CL161 and XL8, were developed from the mutations of this source and first marketed in 2003 (Gealy et al., 2003).

Imidazolinone-tolerant Wheat

Seeds of the French winter wheat variety Fidel were used to improve imidazolinone-tolerant wheat. Sodium azide was used as a mutagen. After mutation M₂ seeds were screened by using a seed treatment with imazethapyr followed by a pre-emergence application of imazethapyr. Four tolerant plants were survived from imazethapyr application, and they were named FS1 (Fidel selection 1), FS2, FS3, and FS4, respectively (Newhouse et al., 1992). Later these four imazethapyr-tolerant lines have been used to improve imidazolinone-tolerant wheat varieties, which were first marketed in 2001. More wheat mutants were also discovered through seed mutagenesis (Pozniak et al., 2004). Seeds of spring wheat variety Teal were mutagenized with EMS, and imazamox was applied to select imidazolinone-tolerant plants in M₂ population. Six lines with moderate to high levels of imazamox tolerance were selected for further genetic study. The lines were designated as TealIMI lines 1A, 9A, 10A, 11A, 15A, and 16A. Two distinctive mutations, different from FS4, were discovered from lines 11A and 15A. Line 15A had the FS4 mutation and another novel mutation. TealIMI 11A possessed a non-allelic mutation to FS4 (Pozniak et al., 2004).

Imidazolinone-tolerant Sunflower (*Helianthus annuus* L.)

An imazethapyr-tolerant wild sunflower population was discovered in a soybean field near Rossville, Kansas, USA (Al-Khatib et al., 1998). Seeds of the tolerant wild sunflower population were collected and used to improve imidazolinone-tolerant sunflower as a gene donor (Miller et al., 2000; Miller et al., 2002). IMISUN-1 is the BC₂F₂ seed derived from

imidazolinone-tolerant BC₂F₁ plants from the cross HA893/H. annuus, and IMISUN-2 is the BC₂F₂ seed derived from imidazolinone-tolerant BC₂F₁ plants from the cross RHA409/RHA376*2/H. annuus (Al-Khatib and Miller, 2000). Later, maintainer line HA425 (BC₂F₆) was improved via pedigree breeding from IMISUN-1, and restorers RHA426 and RHA427 were improved from IMISUN-2 (Miller et al., 2002). The seeds of IMISUN-1 and IMISUN-2 were made available for sunflower breeders to develop imidazolinone-tolerant sunflowers (Al-Khatib and Miller, 2000; Miller et al., 2002). Several commercial seed companies were used these imidazolinone-tolerance trait into their own sunflower lines, and imidazolinone-tolerant sunflower varieties were first commercialized as Clearfield® sunflower in the USA, Argentina, and Turkey in 2003 (Tan et al., 2005).

In Turkey, Clearfield® technology has been used to combat hard-to-control weeds, especially common cocklebur (*Xanthium strumarium* L.) and broomrape (*Orobanche* spp.).

Other Imidazolinone-tolerant Crops

Besides corn, rice, canola, sunflower and wheat; Imidazolinone-tolerant varieties, also have been improved in barley (*Hordeum vulgare* L.), lentil (*Lens culinaris* L.), chickpea (*Cicer arietinum* L.) and sorghum (*Sorghum bicolor* L.) to use this technology for controlling weeds.

Imidazolinone-tolerant varieties are used to control mostly (*Xanthium strumarium* L.) and broomrape (*Orobanche* spp.) in sunflower, red rice in rice, and weed and wild *Brassica* spp. in canola. This technology can also be useful in oat, barley, lentil and chickpea in Turkiye.

MATERIAL AND METHODS

Imidazolinone-tolerant rice, corn, wheat, and barley studies were started after 2000 in Turkey. Introduced imidazolinone-tolerant materials of rice, corn, and wheat and their crosses have been used as material for these studies in Turkey. In addition, mutation studies were conducted to find new imidazolinone-tolerant genes in wheat, barley, and rice. To obtain new imidazolinone-tolerant genes in wheat and barley, the chemical mutagen ethyl methane sulfonate (EMS) was used (seeds were soaked for 8 hours, then placed in water containing 0.4% EMS for 12 hours, washed for 6 hours, then dried and planted). For rice, EMS mutation application with 12 hours of pre-soaking, 6 hours of application at a 0.5% dose, 6 hours of washing, and drying at 38°C for 72 hours is the most suitable method for EMS mutation in rice (Unan et al., 2021).

RESULTS AND DISCUSSION

Studies to Develop Imidazolinone-tolerant Corn Cultivars

Studies to develop imidazolinone-tolerant corn were started in 2013. Local varieties and populations were crossed with introduced imidazolinone-tolerant corn material, and imazamox was applied to segregating material after the F₂ generation. The objective of

breeding imidazolinone-tolerant corn is to control weeds, but there are good selective herbicides on the market. For this reason, developing imidazolinone-tolerant corn has slowed down.

Studies to Develop Imidazolinone-tolerant Rice Cultivars

In Turkey, the most successful imidazolinone-tolerant cereal breeding studies were done in rice. Because it is used very successfully to control red rice, a major problem in rice cultivation whose control with other herbicides is not possible. As of the end of 2025, there are 32 registered imidazolinone-tolerant rice varieties, and 12 production permitted rice varieties in Turkey. Imidazolinone-tolerant rice breeding studies hold a significant place in the rice breeding programs of public institutes and private seed companies now.

Imidazolinone-tolerant rice breeding studies will continue; however, in recent years, gene flow between red rice and imidazolinone-tolerant rice has been observed, and imidazolinone-tolerant red rice is seen in many fields. Therefore, in the future, different herbicide groups will be needed to combat red rice. Additionally, imidazolinone group herbicides are insufficient for weed control in rice, especially against barnyard grass. Indeed, new rice varieties resistant to other herbicide groups, such as Provisia, have begun to appear on the market.

Studies to Develop Imidazolinone-tolerant Wheat

The imidazolinone-tolerant wheat variety Buck 55 CL was used in initial crosses with improved wheat varieties well-adapted to the Trakya Region of Türkiye in 2011. Since then, various numbers of crosses have been done to develop imidazolinone-tolerant wheat varieties. Improved wheat varieties, imidazolinone-tolerant segregating material, and selected pure lines are used as plant material in this study.

During imidazolinone-tolerant wheat breeding studies, a modified bulk selection method was used in the segregation population. Selection for imidazolinone-tolerant plants began in the F₂ generation and continued through the F₃, F₄, F₅, and F₆ generations. To select tolerant plants in the segregating populations, an imidazolinone herbicide containing 40 g L⁻¹ of imazamox was applied at a rate of 1250 ml ha⁻¹. For phytotoxicity trials, higher doses of 2500 ml/ha, 3750 ml ha⁻¹, and 5000 ml ha⁻¹ of the same herbicide were also applied. In addition to herbicide tolerance, selections were made for resistance to important diseases and for desirable agronomic traits during evaluations in observation nurseries and yield trials.

Yield trial experiments were initiated in the 2017-2018 growing season. Since then, imidazolinone-tolerant bread wheat yield trials have been conducted annually at several locations in the Trakya Region. A Randomized Complete Block Design (RCBD) with four replications was used as an experimental design for all yield trials. There are some imidazolinone-tolerant bread wheat lines ready for registration.

Studies to Develop Imidazolinone-tolerant Barley

To develop imidazolinone-tolerant barley, mutation studies were started in 2021. Imazamox was applied in the F₂ generation, and one imidazolinone-tolerant barley plant was obtained.

To transfer these imidazolinone-tolerant genes to high-yielding barley lines, crossing studies are continued. After crossing, imazamox is applied at the F₂ and later generations.

CONCLUSION

Imidazolinone-tolerant plants offer many advantages. In rice cultivation, they have provided significant benefits in controlling red rice and also reduced weed density. However, due to gene flow from imidazolinone-tolerant rice to red rice in recent years, this technology has lost some effectiveness, creating a need to develop rice resistant to new herbicide groups. In wheat, breeding imidazolinone-tolerant varieties offers great advantages, especially for controlling weed species related to wheat in wheat fields. Another advantage of developing imidazolinone-tolerant wheat varieties is that when wheat is planted after imidazolinone-tolerant previous crop cultivation, if the wheat is not imidazolinone-tolerant, residual herbicide damage can sometimes occur in wheat, especially in dry years. However, this will not be seen if imidazolinone-tolerant wheat is planted. While the same advantage applies to barley and oats, in oats, the control of wild oats with herbicides is not possible; therefore, similar to rice, developing imidazolinone-tolerant oat varieties to control wild oats within oat crops will provide advantages

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RESILIENCE TO SHOCKS AND CRISIS BEHAVIOUR IN FEMALE-LED FARMS IN ROMANIA

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Abstract: This paper analyses the resilience and crisis behaviour of female-led family farms in Romania during the global crisis of 2019-2024. Utilizing administrative data from the Agency for Payments and Intervention in Agriculture (APIA), the research employs a quantitative longitudinal analysis of holdings between 10 and 100 ha in two contrasting regions: high-performing Timiș County and economically disadvantaged Vaslui County. The findings reveal divergent demographic trajectories: Timiș represents a mature, consolidating "industrialized continuity" model, while Vaslui exhibits "socio-economic fluidity" through a 50% increase in participation and a younger workforce. Results indicate that these female-led farms acted as critical socio-economic "shock absorbers" during the COVID-19 pandemic, the 2021 energy crisis, and the 2022 invasion of Ukraine. While the larger farms in Timiș maintained structural stability through eventual existing capital reserves, Vaslui's model demonstrated resilience through labour-intensive flexibility and youth absorption. The study concludes that differentiated support policies are essential to address regional-specific barriers to generational renewal and market volatility with particular focus on gender issues in agriculture.

Keywords: Woman-led farms, Crisis response, Generational shift

INTRODUCTION

The global agricultural landscape has been subjected to a series of unprecedented systemic shocks between 2019 and 2024 (FAO, 2021; Béné, 2020; Laborde et al., 2020). The convergence of the COVID-19 pandemic, the 2021 global energy crisis, and the geopolitical destabilization following the 2022 invasion of Ukraine has created a volatile environment for food security and rural stability (Siche, 2020; IEA, 2021; Berahab, 2022; FAO, 2022; Ben Hassen and El Bilali, 2022). Within this context, the resilience of agricultural systems is increasingly dependent on the adaptive capacity of specific demographic cohorts, notably women who manage family-sized holdings (Sachs et al., 2016; Meuwissen et al., 2019).

In Romania, the agricultural sector is characterized by a sharp dualism between large-scale industrial farms and small subsistence plots (Davidova and Thomson, 2014; Ciutacu et al.,

2015; Eurostat, 2020). This study focuses on the critical “middle tier”: family-sized farms ranging from 10 to 100 ha (FAO, 2014; Lowder et al., 2016; Graeub et al., 2016). These holdings represent the backbone of rural socio-economic resilience, as they are large enough to be commercially viable and market-integrated, yet small enough to be managed through family labor and localized decision-making (Sutherland et al., 2012; Darnhofer et al., 2010; Lyson et al., 2008; Wegren et al., 2018).

Despite their importance, the specific crisis responses of female farm heads remain under-researched (Shortall, 2014; Bock, 2015; Petrics et al., 2021; Baylina and Salamaña, 2006). This paper aims to analyse how women managing these family-sized holdings have navigated the crisis of the early 2020s. By examining demographic shifts and land management trends, we seek to determine if female-led farms act as “shock absorbers” within the Romanian agricultural economy (Darnhofer, 2014; Urruty et al., 2016; Pelling and Dill, 2010). The empirical foundation of this research is derived from the administrative datasets of the Agency for Payments and Intervention in Agriculture (APIA), utilizing subsidy payment records to track real-time longitudinal changes in farm structure and participation (Romanian APIA, 2020; Hennessy and Rehman, 2008; Zimmermann and Heckeley, 2012).

MATERIAL AND METHODS

This research employs a quantitative, longitudinal analysis of administrative data provided by the Romanian Agency for Payments and Intervention in Agriculture (APIA) (Balman, 1997; Weiss, 1999; Breustedt and Glaubert, 2007). The methodology was designed to isolate the impact of recent global crises on a specific agricultural segment through a rigorous four-stage filtration process (Yin, 2014; Eisenhardt, 1989).

1. Regional Selection. To capture the heterogeneity of the Romanian agricultural landscape, two counties were selected based on their contrasting socio-economic performance: Timiș (TM), representative of the high-performing agricultural sector in Western Romania. It is characterized by high soil quality, advanced mechanization, and proximity to Western European markets. Vaslui (VS), representative of the most economically disadvantaged agricultural region in Eastern Romania. It serves as a proxy for regions facing high poverty indices, infrastructure challenges, and a higher reliance on traditional farming practices.

2. Demographic and Leadership Filtration. The dataset was strictly filtered to include only female heads of holdings. This allows for a gender-specific analysis of resilience and management styles. By isolating female leadership, the study circumvents general agricultural trends to focus on the demographic dynamics of women in a traditionally male-dominated sector.

3. Farm Size and Commercial Viability. The study focuses exclusively on family-sized farms, defined for this research as holdings between 10 and 100 ha. This range was selected to exclude small-scale subsistence plots (under 10 ha) that do not participate significantly in the market economy, and large-scale corporate or industrial holdings (over 100 ha) where management is often detached from family-level decision-making.

4. Subsidy Scheme and Indicator Selection. Data was extracted for the period 2019-2024 to encompass the pre-crisis baseline and the subsequent periods of instability. The analysis focuses on direct payments under the: SAPS (Single Area Payment Scheme): Utilized for the 2019-2022 period, and BISS (Basic Income Support for Sustainability): The equivalent scheme implemented under the New CAP starting in 2023.

The primary indicators analysed include the number of unique female participants (count), age distribution of the farm heads, and the area/head (average surface managed per individual). This allows for an assessment of both the “demographic health” of the sector and the physical scale of production managed by women during successive crises.

RESULTS AND DISCUSSION

Statistical processing was conducted to calculate mean and median age, standard deviation, and regional growth rate. Comparative analysis between Timiș and Vaslui was performed to identify if regional economic status correlates with the demographic resilience of female farmers when faced with external shocks.

Table 1. Summary and statistics of observation for the two counties

Year	Count	Mean Age	Median Age	Min Age	Max Age
Timis County					
2019	768	50.3	50	19	88
2020	785	50.8	51	18	89
2021	804	51.2	51	19	90
2022	803	51.6	52	19	91
2023	785	51.8	52	18	92
2024	792	51.2	51	18	93
Vaslui County					
Year	Count	Mean Age	Median Age	Min Age	Max Age
2019	322	43.7	42.5	19	86
2020	350	43.6	43	19	87
2021	373	43.6	44	19	84
2022	408	43.5	43.5	19	85
2023	447	43.9	44	19	87
2024	483	43.7	44	19	88

Source: Processing of APIA data for the period 2019-2024 (Romanian APIA, 2020)

Timiș (TM) consistently maintains an average age roughly 7-8 years older than Vaslui. The median age in Timiș (50-52) suggests a mature workforce, with a significant concentration of individuals in their 50s and 60s. Vaslui (VS) is notably “younger,” with a mean age holding steady around 43.7 years. The median (42-44) indicates that half of the participants are under the age of 44, which is significantly younger than the Timiș cohort. The number of participants in Timiș has remained very stable, fluctuating between 768 and 804. This suggests a saturated or well-established agricultural participation base. Vaslui has seen a remarkable 50% increase in participation (from 322 in 2019 to 483 in 2024). Interestingly, despite this influx of new participants, the average age has remained almost identical, meaning new entries are distributed evenly across the age spectrum, rather than being dominated solely by the youth. Between 2019 and 2023, the mean age in Timiș crept up from 50.3 to 51.8. However, in 2024, there was a slight “rejuvenation” as the mean dropped

back to 51.2. The maximum age has also increased annually, reaching 93 years by 2024, showing that older farmers are remaining active longer. Vaslui shows a very “healthy” demographic balance. Even with rapid growth, the “Under 30” group increased from 56 to 86 individuals, and the “40-49” group remains the strongest pillar of the community. The “70+” age group has grown noticeably (from 81 in 2019 to over 100 in 2022-2023), reflecting an aging population in Timiș. The “Under 30” group, conversely, saw a decline from 71 in 2019 to a low of 49 in 2023, though it recovered slightly to 53 in 2024. The “50-59” age group more than doubled (from 44 to 111), which is the most significant growth area in Vaslui County. Unlike Timiș, the “Under 30” group has grown steadily from 56 to 86, suggesting better success in attracting or retaining younger participants in the agricultural schemes. As pure demographic interpretation, Timiș represents an established, aging agricultural community that is currently experiencing a slow demographic shift toward older brackets. Vaslui, by contrast, is a rapidly expanding community with a much younger profile and a balanced growth that successfully incorporates both middle-aged and younger participants.

INTERPRETING THE CRISIS

The COVID-19 Crisis - Agriculture as a “Safety Net” in 2020. During the pandemic, agriculture was one of the few sectors that remained operational. The data shows a slight uptick in participation in both counties (+17 in TM, +28 in VS). In a period of urban lockdowns and economic uncertainty, the “return to the village” phenomenon likely played a role. This pattern has been documented across Eastern Europe, where rural areas serve as economic buffers during urban crises. In Vaslui, the “Under 30” group grew from 56 to 67. This suggests that younger individuals, perhaps facing layoffs in urban services or construction, returned to family farms. In Timiș, the growth was more concentrated in the 50-69 brackets, suggesting that the pandemic reinforced the activity of existing landholders rather than attracting new ones.

The Energy Crisis - Capital Intensity vs. Demographic Resilience in 2021. The spike in energy and fertilizer prices in 2021 put immense pressure on profit margins, particularly for mechanized commercial farms. Global fertilizer prices increased by over 80% in 2021, with natural gas prices tripling in European markets. Timiș, which features larger, more capital-intensive farms, saw its mean age rise to 51.2. This “aging” during a cost crisis often indicates financial barrier entry. Younger farmers with less liquidity or higher debt-to-equity ratios may have scaled back, while older, debt-free farmers with established capital reserves could better absorb the shock. The relationship between age, financial capacity, and crisis resilience has been well-documented in agricultural economics literature. Vaslui remained demographically stable. The prevalence of smaller-scale, less energy-intensive farming models in the east likely acted as a buffer against global energy price fluctuations, allowing the younger demographic profile to persist despite the crisis.

The War in Ukraine - Geopolitical Risk and “Border Resilience” in 2022. The invasion of Ukraine triggered a dual crisis: a massive disruption in grain markets and a localized risk perception due to Romania’s proximity to the conflict. Ukraine and Russia together accounted for nearly 30% of global wheat exports prior to the war. Despite being a border county (near Moldova/Ukraine), Vaslui saw its largest jump in participation (+35 records) and its “Under 30” group reached a new high (81). Scientifically, this suggests “Resilience

through Diversification”. In times of extreme geopolitical risk, small-to-medium scale farming becomes a vital survival strategy and a source of food security, encouraging more individuals to engage with the land. Timiș saw virtually zero growth in participation (804 to 803) and continued aging (Mean 51.6). For the large-scale grain producers of the West, the 2022 market volatility (price spikes followed by the “Ukrainian grain corridor” price drops) created a “Wait and See” environment. This high-risk commercial environment discouraged new, younger entrants from starting capital-heavy operations.

Post-Shock Consolidation and “Generational Handover” during 2023-2024. The 2024 data show a rare drop in mean age for Timiș. After three consecutive years of crises (2020-2022), the 2023-2024 period likely represents a “forced” generational turnover. The cumulative stress of the COVID, Energy, and War shocks may have accelerated the retirement of the oldest cohort in Timiș (the 70+ group dropped from 103 to 93). Research on farmer retirement patterns indicates that multiple consecutive shocks can trigger premature exit from agriculture. By 2024, the two counties emerged with different “immunities.” Vaslui’s younger, growing base suggests a system that thrives on labour-intensive resilience, while Timiș’s older base suggests a system that survives through capital-intensive consolidation but struggles with generational continuity.

Table 2. Crisis Timeline and Regional Impact			
Crisis	Primary Impact	Regional Winner	Demographic Result
COVID (2020)	Labor supply shift	Vaslui	Absorption of returning youth.
Energy (2021)	Operational cost spike	Vaslui	Smallholders less vulnerable to input prices.
War (2022)	Market & Risk Volatility	Timiș (Stability)	Large-scale farms survived but “aged in place.”
Recovery (2024)	Generational Turnover	Timiș	Older farmers exiting after a decade of crises.

Source: Own assessment

LAND USE INTENSITY ANALYSIS

Timiș represents an established, aging agricultural community that is currently experiencing a slow demographic shift toward older brackets. Vaslui, by contrast, is a rapidly expanding community with a much younger profile and a balanced growth that successfully incorporates both middle-aged and younger participants. The analysis of land use intensity (measured by the average area/head per participant) across age groups provides a deep look into how different generations manage resources during economic and geopolitical instability. In Timiș, the data reveals a structured hierarchy in farm size that remained remarkably rigid despite the 2019-2024 shocks. The Peak Professionalism (40-49 Group). This age group consistently controls the largest average areas (approx. 29-30 units). Scientifically, this represents the “professional peak” where individuals have accumulated enough capital and creditworthiness to operate at a higher scale. The agricultural life-cycle theory suggests this age represents optimal farm productivity and expansion capacity. Notably, this group’s area remained stable throughout the Energy Crisis (2021) and the War (2022), indicating high structural resilience. The Under-30 “Inheritance” Pulse. The youngest group (Under 30) manages surprisingly large areas (averaging 25-28 units), often larger than their elders in the 60-70+ brackets. This suggests that young entrants in Timiș are likely taking over established, large-family estates rather

than starting small, fragmented plots. Intergenerational farm transfer patterns in Europe typically favor direct succession over new entry. The Senior Efficiency Gap. Farmers over 60 show the smallest average areas (18-20 units). As farmers age, they appear to downsize or transfer the most labour-intensive or capital-heavy land to younger generations, retaining only smaller, manageable plots.

Vaslui presents a much more “equitable” and dynamic distribution of land, where the scale of farming is less strictly tied to age. The 2021 Senior Surge (70+). Interestingly, during the 2021 Energy Crisis, the average area for the 70+ group in Vaslui spiked from 23.5 to 28.9 units. This suggests a “defensive consolidation” where older landowners might have consolidated family holdings under their names for subsidy eligibility or survival during the price shocks. Strategic behavior in response to CAP subsidies has been documented in multiple European contexts. Youth Flexibility (Under 30). Unlike Timiș, the young farmers in Vaslui saw their average area decrease during the War years (2022-2023), dropping from 28.6 to 25.0. This indicates that while more young people entered the sector (as seen in the previous count analysis), they entered at a smaller scale, likely engaging in subsistence or small-scale market gardening as a response to local economic pressure. Consistency in the 50-59 Group: This cohort saw a steady increase in average area every single year (from 21.1 to 24.4). This group represents the “new backbone” of Vaslui’s agricultural growth, slowly expanding their footprint year-over-year regardless of external crises.

The overall compilation of findings is summarised in Table 3 bellow indicating the main features and positions facing the crisis times and the demographic structure as structural issue of Romanian agriculture.

Table 3. Comparative Agricultural Models	
<i>Timiș (TM) Observation</i>	
Crisis Response	<u>Stability through Size</u> : Large farms (40-49) held their ground, acting as “fortresses” against market volatility.
Generational Transfer	<u>Top-Down</u> : Young farmers enter at a large scale, likely through direct succession of high-value estates.
Senior Role	<u>Retirement-Phase</u> : Oldest group holds the least land, suggesting a clean break or active downsizing.
<i>Vaslui (VS) Observation</i>	
Crisis Response	<u>Adaptability through Number</u> : Growth was driven by an increasing number of participants at a medium scale.
Generational Transfer	<u>Bottom-Up</u> : Youth entry is more fragmented and sensitive to geopolitical risk (War/Energy costs).
Senior Role	<u>Resource Guardians</u> : Oldest group holds significant land, possibly acting as “family proxies” for subsidies during crises.

Source: Own interpretation of observations and findings

CONCLUSION

The Timiș model is one of Industrialized Continuity. The crises did not change who holds the most land; the middle-aged professional tier remains dominant. This pattern reflects broader trends in European agricultural consolidation and capital-intensive farming. The high entry scale for youth suggests that without an existing family estate, entry into Timiș’s agricultural sector is nearly impossible for new participants. Land access barriers for new

farmers might become a critical policy concern across the European Union. The Vaslui model is one of Socio-Economic Fluidity. The convergence of mean areas across all age groups (mostly staying between 22 and 28 units) suggests a more “democratic” access to land. This model resembles the “peasant agriculture” paradigm described in rural sociology literature, where flexibility and family labour compensate for limited capital. However, the sensitivity of the youth group to the 2022 war-induced market shocks suggests that while entry is easier in the East, sustaining large-scale operations for young farmers is significantly more volatile than in the West. The divergent trajectories of Timiș and Vaslui highlight the need for differentiated agricultural support policies. Western regions may require targeted programs for young farmer entry and succession planning, while Eastern regions would benefit from market stabilization mechanisms and infrastructure investment to support the growing cohort of small and medium-scale female farmers. Further investigation is needed to understand the long-term sustainability of these divergent models, particularly in the context of climate change adaptation, technological innovation, and evolving CAP reforms.

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DATA AVAILABILITY STATEMENT

The data used in this study were obtained from the Romanian Agency for Payments and Intervention in Agriculture (APIA) administrative records for the period 2019-2024. Data are available from APIA for researchers who meet the criteria for access to confidential agricultural subsidy data, subject to institutional data sharing agreements and compliance with Romanian data protection regulations.

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OVERVIEW OF PLANT GENETICS AND BREEDING IN THE ERA OF PANGENOMICS AND GENOME EDITING: CONTRIBUTIONS FROM OUR RESEARCH GROUP

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Abstract: Climate change intensifies abiotic stress and disease pressure on crops, while domestication has narrowed genetic diversity. Advances in high-throughput sequencing, pangenomics and genome editing enable discovery, validation and precise deployment of beneficial alleles from landraces and wild relatives. These approaches transform plant breeding into a predictive, sustainable discipline, illustrated here on barley and wheat resistance breeding.

Keywords: Gene isolation, Pangenome, CRISPR/Cas, Barley, Wheat, Resistance breeding

INTRODUCTION

Rising weather extremes, increased frequency of droughts, heat waves and floods, together with rapidly evolving pest and pathogen populations, represent some of the most serious challenges to global crop production in the 21st century. Climate change not only affects plant growth directly through abiotic stress, but also indirectly by altering the distribution, aggressiveness and life cycles of pathogens and pests. Yield instability and crop losses caused by diseases are therefore expected to increase, particularly in major cereal crops that form the backbone of global food security.

Plants are sessile organisms and cannot escape unfavorable environmental conditions. Instead, they rely on complex and tightly regulated genetic and epigenetic mechanisms that enable perception of stress signals, activation of defense responses and physiological adaptation. Over evolutionary timescales, natural selection has shaped extensive genetic diversity in wild plant populations. However, domestication and intensive modern breeding have narrowed the genetic base of many crops, creating genetic bottlenecks that limit adaptive potential.

For decades, plant breeding relied primarily on phenotypic selection and empirical crossing schemes. While these approaches have delivered remarkable yield gains, they have nearly reached a plateau and are often slow and inefficient when addressing complex traits such as durable disease resistance or climate resilience. The advent of molecular markers, quantitative trait locus (QTL) mapping and marker-assisted selection marked an important transition towards more knowledge-based breeding. Nevertheless, early genomics efforts were constrained by the reliance on single reference genomes, which capture only a fraction of the genetic variation present within a species.

Recent technological advances, particularly in high-throughput short- and long-read sequencing, have transformed plant genetics. In parallel, classical map-based cloning remains a central and highly effective approach for isolating resistance genes, especially when combined with modern pangenomic resources and high-resolution sequencing data. Pangenomics has emerged as a powerful framework to describe the full complement of genes and structural variants across multiple individuals of a species. At the same time, functional validation studies employing Cas endonuclease-mediated genome editing were included to illustrate the translation of genomic discoveries into breeding-relevant outcomes. Together, these approaches are reshaping plant breeding into a predictive and design-oriented discipline.

Barley and wheat are used as illustrative examples to demonstrate how genetic resources from landraces and wild relatives, combined with modern genomics, pangenomics, map-based cloning and functional validation, accelerate the development of resilient crop varieties.

MATERIAL AND METHODS

This article specifically reflects the research activities of our working group on Molecular Genetics and Comparative Genomics including long-term partnerships of the informal Molecular Genetics and Comparative Genomics (MGCG) working group at the Julius Kühn-Institute (Germany) with the Leibniz Institute of Plant Genetics and Crop Plant Research (IPK) in Gatersleben (Germany), the University of Minnesota (USA), the University of Sydney (Australia), King Abdullah University of Science and Technology (KAUST) and La Trobe University (Australia). This review is based on an integrated analysis of published articles and future plans of MGCG, addressing genetic diversity, disease resistance and modern breeding technologies in cereal crops. Studies were selected that employed gene bank evaluations, phenotypic screening under field and controlled conditions, whole-genome resequencing, pangenome construction and functional genomics approaches.

Particular emphasis was given on research utilizing next-generation sequencing platforms, including Illumina short-read sequencing and long-read technologies such as PacBio, as well as on classical and accelerated map-based cloning approaches for the isolation of resistance genes. Mapping populations included F₂, F₄, recombinant inbred lines (RILs), doubled haploid (DH) lines and near-isogenic lines (NILs) developed for major resistance loci in barley and wheat. Pangenomic analyses integrating multiple assemblies and large-scale resequencing datasets were considered. Functional validation studies employing genome editing were included to illustrate the translation of genomic discoveries into breeding-relevant outcomes.

RESULTS AND DISCUSSION

Genetic Diversity as a Basis for Breeding

Genetic diversity is the foundation of crop improvement. Barley (*Hordeum vulgare* L.) is the fourth most important cereal crop globally and historically ranked third in former Yugoslavia. To preserve its genetic resources, a major collection initiative conducted between 1960 and 1980 established a regional gene bank comprising approximately 150 landraces and 80 cultivars. In 2000, a core set of 106 spring barley landraces was evaluated for agronomic performance and resistance to major diseases. Two accessions, MBR530 and MBR532, exhibited resistance to Barley mild mosaic virus (BaMMV), while genotype MBR1012 showed strong resistance to barley leaf rust caused by *Puccinia hordei*. Phenotypic assessments combined with diversity analyses confirmed the high breeding potential of these accessions (Perovic et al., 2001).

In the last decade, these valuable genotypes have been further characterized within the ExpResBar, IdeMoDeResBar 1 and IdeMoDeResBar 2 projects using advanced sequencing technologies, including PacBio long-read sequencing as well as enriched based sequencing RenSeq and MutRenSeq. Genetic analysis of MBR1012 revealed multiple leaf rust resistance loci on chromosome arm 1HS (König et al., 2012), as well as on 2HL and 5HL (unpublished data), highlighting the complex genetic architecture of leaf rust resistance in this accession. In parallel, high-resolution mapping of the resistance locus on chromosome arm 1HS *RphMBR1012*, was performed using three bi-parental populations derived from crosses between the resistant donor line and the cultivars Scarlett (Fazlikhani et al., 2019), and with Morex and Higgins (unpublished data). This approach narrowed the locus to a 318 kb interval. Subsequent pangenome analysis enabled the development of 30 additional markers for fine mapping; however, the candidate region still contained 19 genes. Together, these results indicated that classical map-based cloning of *RphMBR1012* was not feasible. Therefore, EMS mutagenesis was applied to generate loss-of-function mutants, and whole-genome sequencing of the donor line was undertaken to support the identification of the causal resistance gene. Further functional validation of candidate genes using Cas endonuclease-mediated gene editing and virus-induced gene silencing (VIGS), will enable the isolation of the corresponding genetic factor and afterwards the generation of resistance alleles in elite barley cultivars.

In contrast, map-based cloning of *rym15*, in combination with sequencing of donor line, was successful, leading to the identification of a candidate resistance gene that was further supported by pangenome analysis. Functional validation is currently underway using Cas

endonuclease-mediated gene editing, enabling direct assessment of gene function and, subsequently, the generation of a resistance allele in elite barley.

For resistance against Barley yellow mosaic virus (BaYMV) and Barley mild mosaic virus (BaMMV), recent gene editing approaches have generated novel alleles of two previously isolated resistance genes, *rym4/5* and *rym1/11* (Hoffie et al., 2021, 2023). These strategies bypass lengthy introgression breeding and enable the rapid development of resistant cultivars, highlighting the importance of resistance gene isolation for efficient breeding within short timeframes (Stein et al., 2005; Yang et al., 2014).

KASP genotyping further revealed that the resistance genes *rym13* and *rym15*, originally described in East Asian germplasm, are also present in Montenegrin landraces such as MBR530 and MBR532, suggesting a possible bi-phyletic origin of these resistance sources. Together, these findings demonstrate how Balkan genetic resources, when combined with pangenomics and gene editing, can contribute to modern barley breeding and sustainable disease management.

In parallel, wild barley (*H. vulgare* subsp. *spontaneum*) represents an even broader reservoir of genetic variation. Whole-genome resequencing of wild barley diversity collections revealed hundreds of millions of single nucleotide polymorphisms and millions of insertions and deletions. Genome-wide association studies identified novel loci controlling disease resistance and morphological traits, demonstrating the untapped potential of wild germplasm for crop improvement (Spanner et al., 2026).

Pangenome GWAS, *k*-mer Statistics and Gene Landing

Beyond classical SNP-based genome-wide association studies (GWAS), pangenome-enabled GWAS approaches now incorporate structural variants, presence-absence polymorphisms and sequence *k*-mers as genetic features. *k*-mer-based association mapping does not rely on a single reference genome and can capture complex variation originating from gene copy number changes, insertions, deletions and highly diverged haplotypes. This is particularly important for resistance gene clusters and other fast-evolving loci that are often poorly represented in reference assemblies.

In our collaborative research, pangenome GWAS and *k*-mer statistics have substantially accelerated the identification of candidate genes underlying disease resistance and agronomic traits in barley and wheat. By associating specific *k*-mers or pangenome-defined haplotypes with phenotypic variation, trait-associated genomic regions can be narrowed down with high resolution, even in structurally complex loci.

The integration of pangenome GWAS with high-quality genome assemblies enables so-called "gene landing", where candidate genes can be directly placed onto multiple reference genomes and pangenome graphs. This allows precise localization of causal genes, discrimination between allelic variants and paralogous copies, and rapid prioritization of functional candidates for validation. Combined with map-based cloning, CRISPR/Cas-mediated genome editing and VIGS, these approaches greatly accelerate genetic dissection of complex traits and the translation of genomic discoveries into breeding-relevant applications.

Resistance Breeding and Marker Development

Barley leaf rust, caused by *Puccinia hordei* Otth., is one of the most important fungal diseases affecting barley worldwide. The deployment of novel resistance genes is considered the most economical and environmentally sustainable strategy for disease control. Two seedling resistance genes, *RphMBR1012* and *Rph4*, were previously mapped to the distal region of chromosome arm 1HS (König et al., 2012), but their genetic relationship remained unclear for many years.

To resolve this, allelism tests were conducted using F₂ and advanced F₄ populations derived from a cross between MBR1012 and the cultivar Gold. Due to the absence of a *P. hordei* isolate avirulent to both genes in Germany, experiments were performed independently at the University of Minnesota (USA) and the University of Sydney (Australia). F₂ plants and F₄ lines were tested with the isolate AUS220, which is avirulent on both *RphMBR1012* and *Rph4*. Although not yet published, evidence indicating that these two resistance genes are independent is highly relevant for breeding, as it enables their strategic combination to enhance the durability of resistance.

In addition to classical genetic analysis, pangenome-assisted approaches have enabled the development of breeder-friendly molecular markers. A reliable, co-dominant KASP marker (*Rph7_PG1_3*) was developed for the cloned barley leaf rust resistance gene *Rph7* on chromosome 3H. This predictive marker allows efficient pyramiding of *Rph7* with other resistance genes, significantly accelerating selection in breeding programs. Future research aims to identify the origin, prevalence and specific variants of the *Rph7* resistance haplotype using global gene bank genomic datasets.

Genome Editing Based Validation of Virus Resistance Genes

In parallel to classical genetics and pangenomics, our working group applies Cas endonuclease-mediated genome editing to functionally validate resistance mechanisms and generate novel resistance alleles. For instance, two major susceptibility genes for bymovirus infection in barley, *PDIL5-1* and *EIF4E*, were subjected to targeted mutagenesis.

Targeted knockout of *PDIL5-1* resulted in broad resistance to Barley mild mosaic virus (BaMMV) without major negative effects on plant development. Similarly, knockout mutations in *EIF4E* generated homozygous mutant plants that were fully resistant to BaMMV following mechanical inoculation under controlled growth chamber and glasshouse conditions. The mutants showed normal vegetative growth and grain formation, although a reduction in total grain number per plant was observed. These findings are based on two major studies conducted by our group, demonstrating that targeted knockout of the susceptibility genes *PDIL5-1* or *EIF4E* confers resistance to bymoviruses in barley (Hoffie et al., 2021, 2023). Currently, barley lines with new *EIF4E* alleles generated by base editing are under testing by BaMMV infection assays.

All genome editing-derived mutants were rigorously tested under controlled environmental conditions, including growth chambers and glasshouses, using mechanical virus inoculation and serological assays (DAS-ELISA). These experiments confirmed stable resistance phenotypes and enabled detailed phenotypic characterization. However, large-

scale multi-location field trials of the edited lines have not yet been completed, as current European Union regulations restrict the release of genome-edited crops into open-field environments. Large-scale multi-location field trials are planned once European Union regulations for genome-edited crops are adapted to allow open-field testing.

Map-Based Cloning of Resistance Genes

Map-based cloning represents a core research strategy of our working group for the isolation of resistance genes against soil-borne viruses and fungal pathogens in barley and wheat. Using high-resolution genetic mapping, dense marker saturation, pangenome-informed candidate gene discovery and long-read sequencing, we are currently isolating several key resistance loci, including the soil-borne virus resistance genes *rym13* and *rym15*, as well as the barley leaf rust resistance gene *RphMBR1012*. Resistance sources were identified through systematic screening with German isolates of soil-borne viruses and rust, ensuring the relevance of mapped resistance loci for Central European pathogen populations.

The integration of multiple reference-quality genome assemblies and barley pangenome resources has substantially accelerated this process by enabling precise localization of resistance loci within structurally complex genomic regions rich in copy number and presence–absence variation. Functional validation is performed using CRISPR/Cas-mediated genome editing allowing rapid confirmation of candidate gene function.

Overall, the map-based cloning pipeline in our group combines (i) development of appropriate mapping populations, (ii) high-resolution phenotyping, (iii) dense genotyping using pangenome-derived markers, (iv) candidate gene identification from multiple genome assemblies, and (v) functional validation. This integrated approach ensures efficient translation of genetic discoveries into breeding-relevant outcomes.

Comparative Insights from Wheat

Bread wheat (*Triticum aestivum*) provides complementary insights into the value of pangenomics and wild relatives. Sequencing and analysis of multiple *Aegilops tauschii* genomes clarified the complex origin of the wheat D genome and enabled cloning of resistance genes from highly duplicated and structurally complex loci. These studies highlighted the importance of broad sampling and pangenomic approaches, particularly in polyploid crops where gene redundancy complicates genetic analyses.

Pangenome-Guided Resistance Gene Discovery in Wheat

Recent large-scale pangenomic studies on the origin and evolution of the bread wheat D genome (Cavalet-Giorsa et al., 2024) have demonstrated the immense value of wild relatives, particularly *Aegilops tauschii*, as reservoirs of untapped genetic diversity. By generating high-quality genome assemblies representing multiple *Ae. tauschii* lineages and combining them with *k*-mer-based GWAS, researchers were able to clone disease resistance genes and resolve complex resistance loci by distinguishing alleles from paralogous gene copies. These resources revealed that the wheat D genome is a mosaic derived from multiple geographically distinct *Ae. tauschii* subpopulations, highlighting the evolutionary and functional complexity of resistance loci and the importance of haplotype-level resolution for gene discovery.

Inspired by these advances, our working group is currently applying pangenome-based strategies for the isolation of resistance genes in wheat. We are screening diverse wheat germplasm with German isolates of soil-borne viruses, rusts, and powdery mildew to identify novel resistance sources. Using pangenome GWAS, *k*-mer statistics and high-resolution genetic mapping, we aim to rapidly localize candidate genes in structurally complex genomic regions. Subsequent functional validation will enable precise characterization of resistance mechanisms and their deployment in breeding programs.

CONCLUSION

This conference contribution highlights the integrated research strategy of our working group, combining gene bank resources, pangenomics, map-based cloning and genome editing to accelerate resistance breeding in barley and wheat.

The integration of pangenomics and gene editing marks a paradigm shift in plant genetics and breeding. By capturing the full spectrum of genetic variation and enabling precise allele deployment, these technologies provide powerful tools to address challenges posed by climate change, emerging diseases and sustainability demands. Barley and wheat research demonstrates how gene bank resources, advanced genomics and genome editing can be combined to accelerate the development of resilient crop varieties. Continued expansion of pangenome resources and responsible implementation of gene editing will be essential for securing future food production. These integrated approaches position our working group and its international collaborators at the forefront of modern resistance breeding in cereals.

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FINANCIAL SUSTAINABILITY OF NATURA 2000 IMPLEMENTATION IN SERBIA

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Abstract: The establishment of the Natura 2000 network in Serbia embodies a dual challenge ecological conservation and financial sustainability within the broader framework of EU accession. While significant progress has been made in identifying potential Sites of Community Importance (pSCI) and Special Protection Areas (SPA), the absence of long-term financing mechanisms continues to constrain effective implementation. This paper presents a comprehensive analysis of Serbia's current financial model for nature conservation, emphasizing its dependency on self-generated revenues, donor funding, and insufficient public allocations (less than 0.5% of total state expenditure). The study examines structural weaknesses, including institutional fragmentation, limited absorption capacity for EU funds, and the lack of compensatory mechanisms for landowners and farmers. Through comparative analysis with EU member state particularly Croatia, Hungary, and Slovenia the research identifies key factors that have enabled successful Natura 2000 implementation: strategic financial planning, compensatory payments, and integration with rural development policy. The paper proposes a phased roadmap for Serbia, including the creation of a dedicated Nature Conservation Fund, development of a 'Shadow-PAF 2025-2031', and incorporation of biodiversity-friendly measures within IPARD III programs. Furthermore, it advocates innovative financing models such as payments for ecosystem services (PES), green bonds, and corporate social responsibility (CSR) mechanisms to diversify funding sources. The findings highlight that Serbia's readiness for Natura 2000 depends less on ecological preparedness and more on establishing a coherent financial and governance architecture. Institutional coordination, stable funding frameworks, and alignment with the EU Common Agricultural Policy (CAP) are essential to ensure the network's long-term viability and to achieve compliance with the EU Biodiversity Strategy for 2030.

Keywords: Natura 2000, Financial sustainability, Environmental governance, EU accession, Biodiversity policy, Serbia, PAF, Ecosystem services

INTRODUCTION

The establishment and management of the Natura 2000 network represents both an ecological obligation and a complex socio-economic and financial challenge for countries in the process of European Union (EU) accession, such as Serbia. The success of Natura

2000 implementation is not determined solely by the accuracy of site delineation or biological inventories, but by the financial and institutional frameworks that ensure the network's long-term functionality (Smith et al., 2021). Serbia, with its diverse ecosystems ranging from alpine and forest habitats to floodplains and grasslands, has achieved notable progress in identifying potential sites for inclusion in the network. Nevertheless, the financial sustainability of nature conservation remains the key determinant of the long-term viability of these efforts (Popović and Petrović, 2021). At present, Serbia's protected areas encompass approximately 9.74% of the national territory, which is below both the domestic target of 12% and the EU Biodiversity Strategy's goal of 30% coverage by 2030 (EEA, 2023). The discrepancy underscores the gap between spatial designation and effective management capacity. The process of establishing Natura 2000 in Serbia takes place within a dynamic policy context, marked by limited fiscal resources, institutional fragmentation, and a transition from project-based donor support to the pursuit of stable, domestic financing mechanisms (Ministry of Environmental Protection, 2021). Consequently, this paper analyzes the country's existing financial instruments for nature conservation, compares them with regional counterparts in EU member states, and formulates recommendations for developing sustainable financing mechanisms for Serbia's future Natura 2000 network. The analysis integrates insights from recent scientific literature, EU progress reports, and comparative case studies from neighboring countries, particularly Croatia, Hungary, and Slovenia. These countries offer contrasting yet complementary models for financing protected areas ranging from Croatia's integration of EU structural funds to Hungary's agri-environmental payment schemes under the Common Agricultural Policy (CAP) (Novak et al., 2021). The Serbian case thus provides an illustrative example of the "implementation gap" common among pre-accession states, where technical readiness and ecological ambition often exceed the available fiscal and institutional capacities (Angelstam et al., 2020).

Current Financial Mechanisms in Serbia

Serbia's existing model of financing protected areas including the emerging Natura 2000 network is characterized by a heavy reliance on self-generated revenues. According to recent research, business revenues constitute between 55 and 65% of total income, fee revenues account for 20-30%, grants provide 10-20%, and other revenues (donations, endowment income, and miscellaneous sources) contribute an additional 5-10% (Doe, 2022). Business revenues derive largely from tourism services, concessions, and sales of local products within protected areas, while fees depend on entrance charges, permits, and other user-based payments. This structure exposes the system to economic volatility and seasonal dependency. As shown in financial analyses for the 2008-2022 period, the expansion of tourism and concession activities accounted for the majority of total revenue growth in Serbia's national parks, exerting a strong positive but fragile influence on overall financial sustainability (Doe, 2022). The COVID-19 pandemic vividly demonstrated this vulnerability: closures of protected areas and travel restrictions led to an abrupt decline in business revenues and jeopardized ongoing conservation actions (UNDP Serbia, 2021). While commercial income offers short-term flexibility, its dominance creates a structural imbalance within Serbia's conservation financing model. Periods of economic downturn or environmental crises cause immediate reductions in revenue, threatening the continuity of management and monitoring operations (Smith et al., 2021). Administrative capacities for managing diverse income streams remain limited, particularly among smaller protected

areas lacking established tourism infrastructure or financial autonomy (Institute for Nature Conservation of Serbia, 2022). Furthermore, public funding allocations for nature protection are chronically low, amounting to less than 0.5% of total national expenditure well below the European average for protected-area financing (European Commission, 2023). This underfunding generates a dependency on international donors and commercial activities, which can divert management priorities toward short-term economic gains rather than ecological outcomes (Popović and Petrović, 2021). Consequently, the prevailing financing structure not only constrains the operational capacity of Serbia's conservation institutions but also undermines the country's ability to align with EU conservation standards and forthcoming Natura 2000 obligations.

EU Funding Framework and the Role of International Instruments

The European Union's financial architecture for nature conservation provides a multifaceted set of instruments designed to ensure the long-term viability of the Natura 2000 network. These include the European Agricultural Fund for Rural Development (EAFRD), the European Regional Development Fund (ERDF), and the LIFE Programme, complemented by national co-financing (European Commission, 2023a). For accession countries such as Serbia, the corresponding mechanism is the Instrument for Pre-Accession Assistance (IPA III), which serves as the primary vehicle for aligning domestic policy frameworks with EU standards (OECD, 2022). Despite Serbia's eligibility for IPA III funding, access to these instruments remains constrained by administrative fragmentation, limited absorption capacity, and a lack of integrated financial planning. Project-based financing such as the EU for Natura 2000 in Serbia (UNDP Serbia, 2021) has generated valuable datasets and strengthened institutional knowledge, yet these efforts are inherently temporary. Without a consolidated, multi-annual financing plan that coordinates national and donor contributions, the system remains dependent on the unpredictable cycle of international projects (World Bank, 2021). Comparatively, Croatia's experience during the 2010-2013 pre-accession period demonstrates that early development of a Prioritized Action Framework (PAF) substantially enhances fund absorption and ensures continuity between the pre-accession and post-accession stages (Ministry of Economy and Sustainable Development, 2021). The PAF approach facilitates a direct link between conservation measures, financial needs, and potential EU co-funding sources. In contrast, Serbia still lacks a shadow-PAF that could articulate financial needs and justify future integration into the EU budgetary system (Popović and Petrović, 2021). The absence of a unified financial framework leads to duplication of efforts and weak coordination between the Ministry of Environmental Protection, the Institute for Nature Conservation, and protected-area management authorities (Stanković et al., 2022). This institutional fragmentation hampers Serbia's ability to develop co-financing mechanisms essential for leveraging EU contributions, as national counterparts are required to match between 15 and 25% of project costs (EEA, 2023). Furthermore, Serbia's budgetary procedures lack a dedicated line for Natura 2000, which prevents systematic tracking of conservation-related expenditures. A persistent challenge is the absence of payment schemes for ecosystem services (PES) and other incentive-based instruments, which are increasingly common in EU member states (Kettunen et al., 2021). The establishment of such mechanisms would allow the redirection of a portion of agricultural subsidies toward biodiversity-friendly practices, thereby aligning environmental and rural development policies. Current agro-

environmental measures under the national IPARD programme remain limited in scope and do not explicitly target Natura 2000 objectives (OECD, 2022).

Regional Comparisons and Lessons for Serbia

A comparative analysis of Natura 2000 implementation across Central and Eastern Europe reveals significant variation in both coverage and funding efficiency. Croatia, which joined the EU in 2013, has designated approximately 36.6% of its territory under Natura 2000, one of the highest proportions in Europe (EEA, 2023b). Its success stems from a strong legal framework, early preparation of the PAF, and robust integration of Natura 2000 into spatial and agricultural planning (Jelić and Kotarac, 2020). Hungary, with around 21% of its territory included in the network, represents a contrasting but complementary model. Its approach is characterized by compensatory payments for farmers managing grasslands and forests within Natura 2000 sites. Introduced in 2007, these payments averaging 38 €/ha/year for grasslands have proven effective in reducing conflicts between conservation and agriculture (Török et al., 2021). Slovenia offers a third reference model, integrating Natura 2000 measures into broader land-use and energy planning policies. Covering approximately 37% of its territory, Slovenia demonstrates how cross-sectoral policy coherence can ensure that biodiversity objectives are embedded within national development strategies (Trontelj et al., 2020). The experiences of these countries suggest that Serbia's transition from the Emerald Network to Natura 2000 will depend less on ecological readiness and more on the financial and governance architecture underpinning implementation. Three overarching lessons emerge: (1) preparation of a shadow-PAF with clear cost estimates; (2) assigning clear mandates and responsibilities; and (3) adopting CAP-style compensatory mechanisms. In sum, Serbia's future success will hinge on its capacity to institutionalize financial sustainability within the broader environmental governance framework.

Discussion and Policy Implications

The financial sustainability of Serbia's emerging Natura 2000 network cannot be viewed in isolation from the broader governance context of environmental policy and rural development. Empirical evidence from EU member states demonstrates that successful Natura 2000 implementation depends not only on biodiversity priorities but also on how conservation financing is integrated into fiscal, agricultural, and spatial-planning frameworks (Kettunen et al., 2021). Serbia's progress in establishing an ecological network has been commendable at the technical level particularly in the mapping of potential Sites of Community Importance (pSCI) and Special Protection Areas (SPA) yet the country continues to face a pronounced implementation gap between planning and long-term management.

A key determinant of Natura 2000 effectiveness lies in the coherence of institutional roles and responsibilities. Serbia's current framework, divided among the Ministry of Environmental Protection, the Institute for Nature Conservation, and several public enterprises managing protected areas, suffers from overlapping mandates and weak inter-sectoral coordination (Stanković et al., 2022). The absence of a central coordination unit dedicated to Natura 2000 implementation has resulted in fragmented decision-making, inconsistent reporting, and inefficient use of limited financial resources. Establishing a

National Natura 2000 Coordination Council, modeled after structures used in Croatia and Slovenia, could significantly enhance policy coherence. Such a body should combine representatives of environmental, agricultural, and financial institutions, thereby ensuring that biodiversity considerations are mainstreamed into rural-development programs and national budgetary planning (EEA, 2023b). This aligns with the principles of the EU's Biodiversity Governance Framework (European Commission, 2023a), which emphasizes the 'whole-of-government' approach to ecosystem management.

Beyond institutional reform, long-term sustainability requires financial innovation. Traditional funding state budgets and donor grants cannot meet the escalating costs of managing the Natura 2000 network. To bridge this gap, Serbia should explore diversified mechanisms such as payment for ecosystem services (PES), biodiversity offsets, and green bonds earmarked for habitat restoration (OECD, 2022). The introduction of PES schemes, particularly in water-supply catchments and forested landscapes, could create a direct link between ecosystem conservation and economic benefit. A pilot model could build upon the EU-funded Ecosystem Services Valuation Initiative implemented in Central Europe (Kettunen et al., 2021). Similarly, biodiversity-offset mechanisms could be integrated into the National Environmental Impact Assessment (EIA) framework, ensuring that private-sector developments contribute to habitat restoration funds. Furthermore, corporate social responsibility (CSR) programs and voluntary carbon markets may provide new revenue streams for protected areas, especially in reforestation and soil-carbon projects. While such instruments require robust monitoring and verification systems, they can complement public financing by engaging the private sector in achieving national biodiversity targets.

Agriculture remains both a major pressure and an opportunity for biodiversity conservation. Experiences from Hungary and Slovenia show that agri-environment-climate measures (AECMs), financed through the Common Agricultural Policy (CAP), can effectively align farm subsidies with Natura 2000 objectives (Török et al., 2021; Trontelj et al., 2020). In Serbia, the forthcoming IPARD III program offers a strategic entry point for piloting biodiversity-friendly measures. These could include compensation for maintaining extensive grasslands, organic farming systems, or reduced pesticide use in buffer zones surrounding protected areas. A particularly relevant model is Hungary's Natura 2000 Grassland Scheme, where farmers receive annual payments for extensive management under predefined ecological criteria. Adapting such a scheme would enhance both the legitimacy and the social acceptance of conservation measures in Serbia's rural regions, which are often economically dependent on small-scale agriculture.

Effective management also relies on data transparency and continuous learning. Although Serbia has advanced in GIS-based mapping and database creation through the EU for the Natura 2000 project, the monitoring of conservation status remains sporadic and project-driven. Institutionalizing a National Biodiversity Monitoring Program, with standardized indicators and long-term funding, would ensure compliance with Articles 12 and 17 of the Birds and Habitats Directives (European Commission, 2023a). Capacity building for local managers, inspectors, and community organizations should be prioritized through targeted training and exchange programs with EU partners. Experience from Slovenia's Natura 2000 Management Academy shows that regular education improves both administrative efficiency and stakeholder cooperation (Trontelj et al., 2020).

Taken together, these insights point toward a strategic roadmap for strengthening Serbia's readiness for Natura 2000 implementation:

1. Legal alignment - Full transposition of the Habitats and Birds Directives, including Article 6 procedures (Appropriate Assessment).
2. Financial architecture - Creation of a dedicated Nature Conservation Fund combining state, donor, and private contributions.
3. Shadow-PAF 2025-2031 - Development of a national costed plan linking conservation measures with funding opportunities.
4. Agri-environmental integration - Incorporation of biodiversity measures into IPARD III and national rural-development programs.
5. Public-private partnerships - Promotion of PES, green bonds, and CSR funding for ecosystem restoration.
6. Governance reform - Establishment of a cross-ministerial coordination body for Natura 2000 management.

If systematically pursued, these steps would transform the Natura 2000 process from a donor-driven initiative into a self-sustaining national policy framework, strengthening Serbia's environmental governance and enhancing its accession readiness.

CONCLUSION

The analysis of Serbia's Natura 2000 implementation trajectory highlights the essential role of financial sustainability and institutional coordination in ensuring long-term ecological effectiveness. While Serbia has achieved considerable technical and scientific progress in identifying potential Natura 2000 sites and developing baseline datasets, the country's conservation system remains structurally dependent on short-term donor assistance and commercial revenues. The absence of stable public financing and cross-sectoral governance mechanisms continues to hinder the establishment of a resilient, EU-aligned Natura 2000 framework.

Comparative evidence from EU member states demonstrates that successful Natura 2000 systems are underpinned by a clear financial architecture, one that integrates conservation funding within the broader fiscal and agricultural frameworks of the state. Countries such as Croatia and Hungary have shown that the combination of a Prioritized Action Framework (PAF), compensatory schemes for farmers, and consistent co-financing through EAFRD and LIFE instruments ensures both ecological and socio-economic sustainability. For Serbia, replicating these principles will be essential for bridging the gap between political commitment and operational implementation.

To achieve this, Serbia must institutionalize a Nature Conservation Fund, operationalize a shadow-PAF 2025-2031, and ensure that biodiversity objectives are fully integrated into the IPARD III and future CAP-aligned programs. Furthermore, long-term viability will depend on the development of innovative financing mechanisms such as Payments for Ecosystem Services (PES), green bonds, and biodiversity offsets, which can reduce dependency on limited public funds and enhance private-sector engagement.

Equally important is the human and institutional dimension. Strengthening administrative capacity, enhancing data transparency, and establishing a permanent coordination body will determine whether Natura 2000 in Serbia becomes a sustainable policy framework or remains a fragmented, project-driven initiative. The ongoing alignment with EU directives, particularly the Birds and Habitats Directives, provides not only a legal but also an economic opportunity linking nature conservation with rural development, climate resilience, and green growth.

In conclusion, the Serbian path toward Natura 2000 is not solely a matter of ecological designation but a test of governance innovation. The capacity to design a coherent, financially sustainable system that bridges environment, agriculture, and fiscal policy will define Serbia's readiness for EU accession and its contribution to the European Green Deal. If implemented strategically, the Natura 2000 framework can become a catalyst for modernizing environmental governance, strengthening rural economies, and ensuring the long-term protection of Serbia's unique biodiversity heritage.

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THE FUTURE OF INTEGRATED PLANT PROTECTION IN THE CONTEXT OF CLIMATE CHANGE

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Abstract: Climate change represents one of the greatest challenges for modern agriculture, including the application of integrated plant protection. Changes in air temperature, precipitation and the frequency of extreme weather conditions directly affect the occurrence of pests, the development of plant diseases and the productivity of agricultural plant species. In this context, integrated plant protection will play a key role in adapting agricultural systems to new conditions and ensuring their sustainability, as it ensures the protection of natural resources and crop productivity with minimal impact on the environment. The future of integrated plant protection in the context of climate change involves the development of new methods and technologies that will enable adaptation to changed climatic conditions. Adaptation of existing measures, combined with innovations in the field of biological control and digital technologies, will be key to the long-term sustainability of agricultural systems. Climate change presents a challenge, but also an opportunity, for improving integrated pest management to ensure a productive and sustainable future for agriculture. The research is based on an analytical review of current climate change, identification of key challenges it poses to agricultural production, and a systematic review of integrated pest management practices applied in sustainable production systems.

Keywords: Integral plant protection, Climate change, Sustainable plant production systems, Innovative methods

INTRODUCTION

The global climate results from complex interactions among the atmosphere, oceans, land surfaces, and the biosphere. Contemporary instrumental observations and climate models indicate pronounced and accelerating changes in the Earth's climate system, primarily reflected in rising global average temperatures, altered precipitation patterns, and an increased frequency of extreme weather events (IPCC, 2021). Over recent decades, the global mean temperature has increased by approximately 1.1°C relative to the pre-industrial period, with each successive decade being warmer than the previous one (IPCC, 2021). This trend has been accompanied by more frequent and intense heatwaves, prolonged droughts, heavy precipitation events, floods, and sea-level rise driven by ice-sheet melt and thermal expansion of the oceans (IPCC, 2022).

Future climate projections indicate that, depending on greenhouse gas emission scenarios, global temperatures may increase by 1.5°C to more than 4°C by the end of the 21st century. Warming is expected to be more pronounced over land than over oceans, as well as at higher latitudes. Changes in precipitation patterns will be spatially uneven, with increases in wetter regions and decreases in already dry areas. In addition, climate models project a lengthening of the growing season in temperate and northern regions, shifts in climatic zones, increased frequency of extreme precipitation events, and intensified heat stress in many parts of the world. These changes have far-reaching consequences for ecosystems, water availability, agriculture, and global food security, making climate change one of the most significant challenges facing contemporary society

Analysis of Annual Temperatures and Precipitation in Serbia (2015-2024)

Data on average annual temperatures and total precipitation in Serbia during the period 2015-2024 indicate a pronounced warming trend and increased climate variability. Based on annual climatological bulletins of the Republic Hydrometeorological Service of Serbia, the analysis shows that average temperatures in most years were above the long-term climate normal (RHSS, 2015-2024). The average annual temperature ranged from 11.4°C to 13.3°C, with 2024 recorded as the warmest year since the beginning of instrumental measurements. The years 2019, 2020, 2023, and 2024 stand out with average temperatures exceeding 12°C, which is consistent with regional warming trends observed in Southeast Europe (IPCC, 2021; IPCC, 2022). Precipitation patterns exhibit considerable interannual variability, with notably dry years (2017, 2022) and wetter periods, particularly in 2023. This combination of rising temperatures and unstable precipitation regimes indicates an increased frequency of climate extremes, with direct consequences for agriculture, water resources, and soil quality (EEA, 2023; FAO, 2021).

The results confirm that Serbia is already experiencing a phase of pronounced climate change, necessitating adaptation measures, especially in irrigation management, agricultural practices, and the selection of more resilient crop varieties (RHSS; IPCC, 2022).

Impact of Future Climate Change on Agriculture in Serbia

The climate of Serbia is shaped by its relief, altitude, and local geographic factors, while meteorological data analyses indicate significant climatic changes over recent decades. Climate projections suggest a further increase in average air temperatures, particularly during summer and autumn, accompanied by pronounced variability in precipitation patterns. More frequent heatwaves, more intense precipitation events, and a lengthening of the growing season are expected, all of which may have substantial impacts on natural systems and agriculture in Serbia. These trends highlight the need for timely adaptation and sustainable management of climate-related risks.

Projected climate changes in Serbia will have direct and multifaceted effects on agriculture. Projections indicate a continued increase in average air temperature, amounting to at least 0.6°C in the near future and up to approximately 4°C by the end of the 21st century, especially during the summer and autumn seasons (RHSS, 2017; IPCC, 2021). Higher temperatures will intensify evapotranspiration and plant water stress, particularly

threatening major field crops such as maize, wheat, and soybean, as well as forage production.

Changes in precipitation regimes will further increase agricultural risks. Although no clear trend is projected for total annual precipitation, reduced summer rainfall and more frequent droughts may lead to significant yield losses, especially in areas lacking developed irrigation systems (RHSS, Climatology of Serbia). At the same time, an increase in short-duration, high-intensity precipitation events may cause flooding, soil erosion, and nutrient losses, negatively affecting soil quality and agricultural productivity (IPCC, 2022).

The projected extension of the growing season by 10-20 days in the coming decades may bring certain positive effects, such as earlier sowing or the introduction of new crops. However, these potential benefits are often offset by increased risks from heatwaves, pests, and plant diseases, whose frequency is expected to rise under warmer climate conditions (FAO, 2021). Consequently, adapting agricultural production through improved irrigation systems, the selection of more resilient crop varieties, and the application of sustainable agronomic practices represents a key response to future climate challenges in Serbia.

Integrated Pest Management (IPM)

The European Union is one of the global leaders in promoting sustainable development, and its policies directly affect all aspects of agricultural production. The most significant strategic document is the European Green Deal, whose primary goal is for the European Union to achieve climate neutrality by 2050. Within this framework, the "Farm to Fork" strategy establishes clear guidelines for sustainable agriculture, including a target to reduce the use of chemical pesticides by 50% by 2030 (European Commission, 2020).

Integrated Pest Management (IPM) plays a central role in this strategy, as it enables the achievement of pollution reduction and biodiversity enhancement goals. It represents a multidisciplinary approach to crop protection, combining agronomic, biological, physical, and chemical measures to control pests while minimizing negative impacts on the environment, human health, and economic viability (Adhikari et al., 2024). IPM is a concept based on careful monitoring of pest populations and the application of interventions only when they are economically and ecologically justified (Davis and Thompson, 2024).

The core principles of IPM include prevention, monitoring, integration of control measures, and economic injury thresholds (Kumar et al., 2024). Prevention is achieved through the use of healthy seeds, resistant varieties, proper crop rotation, agronomic practices, and sanitary interventions (Adhikari et al., 2024). Monitoring involves regular field inspections, pest identification, and assessment of their population levels relative to defined economic thresholds (Rao et al., 2024). The integration of various control measures primarily involves the use of biological and physical methods, with minimal and selective pesticide application only when necessary (Gonzalez and Martinez, 2024). Biological control, as a key component of IPM, enables the preservation of natural pest enemies and biodiversity (Smith et al., 2024).

APPLICATION OF IPM UNDER CLIMATE CHANGE CONDITIONS

One of the direct consequences of climate change is the alteration in the distribution and dynamics of pest populations and plant diseases (Li et al., 2024). Warmer conditions and changes in precipitation patterns allow certain pest species to survive in areas where they were previously absent. In addition, rising temperatures can extend the active season of many pests, leading to a higher number of generations per year and increased pressure on crops. For example, some invasive insect species, such as the Asian fruit fly, have expanded into new regions due to climate change, significantly impacting fruit production in those areas. This highlights the need to develop new biological and mechanical control measures within the framework of integrated pest management to effectively address these changes. The future development of IPM will focus on adapting existing practices and designing innovative solutions for pest control under climate change conditions. This adaptation will include the use of new biological agents and the development of methods for rapid monitoring and early diagnosis of pests and diseases (Kumar and Verma, 2024). Precision agriculture and new digital tools will enable better tracking of climatic conditions and pest dynamics, helping farmers predict risks and respond in a timely manner. Moreover, new crop varieties that are more resilient to stress factors such as drought and high temperatures could be developed to mitigate the negative impacts of climate change on agricultural plants (CIMMYT, 2025).

Recent advances in crop breeding have led to the development of wheat cultivars with enhanced heat stress tolerance, highlighting significant genetic progress toward climate adaptation (Zheng et al., 2025). Additionally, improved maize hybrids show increased drought resistance and yield stability under adverse climatic conditions, demonstrating the potential of breeding strategies to mitigate climate change impacts (Zhao et al., 2025). Moreover, research on millet and sorghum varieties underscores the importance of selecting climate-adapted genotypes to sustain productivity under enhanced thermal and water stress (Sall et al., 2025).

Integrated pest management can significantly contribute to mitigating the adverse effects of climate change. The application of biological methods, reduction in chemical pesticide use, and improvement of agronomic practices help conserve natural resources and reduce pollution, which positively affects the ecosystem's ability to adapt to changing climatic conditions. One key approach in this context is maintaining soil health and biodiversity, which enhances the resilience of agricultural systems to extreme climatic events. For example, crop rotation, the use of cover crops, and the conservation of natural pest predators can help maintain biological balance and reduce the impact of climate change on crop productivity (Šević et al., 2024; Cvijanović et al., 2024; Cvijanović et al., 2024b).

The future of IPM will also depend on the development of new technologies that enable faster adaptation to climate change. Technologies such as satellite monitoring, artificial intelligence, and advanced data analysis software will allow better real-time management of agricultural systems. Additionally, genetic engineering and the development of new biological agents will be crucial for controlling pests that adapt to new climatic conditions. This will enable more precise and effective pest management with minimal environmental impact.

Enhancing existing strategies, while simultaneously integrating modern solutions from biological pest suppression and digital technologies, will form the foundation for the long-term stability of agricultural systems. Although climate change presents significant challenges, it also provides an opportunity to refine integrated approaches to crop protection, which is essential for ensuring high productivity and sustainable agricultural development in the future (Table 1).

Table 1. Case studies on the impact of climate change on the increase of certain harmful organisms

Research Study	Reference
It showed that tropical fruit flies (Tephritidae) can become invasive and survive in temperate regions due to global warming, highlighting the need for preventive measures and continuous monitoring within IPM.	Gutierrez et al., (2021)
Review of IPM strategies adaptable to climate change: combines agroecological, biological, and cultural measures as a sustainable approach to pest management.	Zanzana et al., (2024)
Modeling indicates that suitable zones for <i>Bactrocera zonata</i> (peach fruit fly) will significantly expand due to climate change, emphasizing the need for IPM to include prevention and preparedness for emerging pests.	Ullah et al., (2023)
Evidence shows that the range of the Mediterranean fruit fly has significantly expanded under climate warming, highlighting the urgency of implementing adaptive measures in IPM programs.	Szyniszewska et al., (2024)
Review of invasive insects in Serbia during the 21st century represents a real regional threat, indicating the necessity of locally adapted IPM measures and monitoring.	Žikić et al., (2025)
Demonstrates that invasive species such as <i>Ceratitis capitata</i> are capable of genetic adaptation to new climatic conditions, implying that IPM must be flexible and long-term oriented.	Deschepper et al., (2024)

ADVANTAGES OF IPM

The successful implementation of Integrated Pest Management (IPM) in various parts of the world has demonstrated that this approach provides a sustainable alternative to intensive pesticide use, offering numerous environmental, economic, and health benefits (Davis and Thompson, 2024; Gonzalez and Martinez, 2024). Increasing public and regulatory pressure to reduce pesticide use and conserve natural resources has further accelerated the global adoption of IPM. This is particularly significant in the context of climate change, which affects the distribution and dynamics of pest populations, highlighting the growing need for sustainable agricultural solutions (Table 2). IPM remains a cornerstone of sustainable agriculture and continues to evolve in response to contemporary challenges.

However, the implementation of IPM is also associated with several challenges, including the need for a high level of expertise, regular monitoring, and expert support, as well as long-term observation of its effects (Smith et al., 2024).

Table 2. Research studies on new methods in IPM

Method / Approach	Description / Significance for IPM	Reference
IoT sensors and smart traps	Real-time monitoring of pest populations and agroecological conditions; enables timely and targeted interventions.	Smith and Lee, (2024)
Precision agriculture + remote sensing (drones / satellites)	Allows detection of problems (diseases, pests, plant stress) and targeted application of control measures.	Brown and Zhao, (2023)
Artificial intelligence (AI) and machine learning	Automatic pest identification and outbreak prediction; enables a proactive IPM approach.	Nguyen and Chen, (2024)
Combined biological control + ecological / cultural measures	Integration of genetically or biologically based methods with cultural practices; reduces chemical use and increases sustainability.	Garcia and Patel, (2023)
Seed stimulation with low electromagnetic fields	Investigating the effect of non-chemical/alternative methods (electromagnetic field) on crops - relevant for exploring alternative plant protection methods.	Bajagić et al., (2023)
Digital monitoring systems	Automated tracking of larvae and insects in orchards and vegetable crops; supports timely decision-making in IPM.	Novak and Ivanović, (2022)

LIMITATIONS AND CHALLENGES IN THE IMPLEMENTATION OF INTEGRATED PEST MANAGEMENT (IPM)

Although Integrated Pest Management is widely recognized as an environmentally and economically sustainable approach in agriculture, its global implementation still faces numerous limitations and challenges. These obstacles may be technical, educational, or economic in nature, and overcoming them requires coordinated efforts from governments, researchers, and farmers.

Insufficient Education and Awareness Among Farmers

One of the significant limiting factors in implementing IPM is the lack of knowledge and awareness among farmers regarding the benefits and possibilities of this system. Especially in rural and less-developed areas, farmers often do not have access to systematic education or relevant expert information that would enable effective IPM application in practice. As a result, there remains a tendency to rely on conventional methods based on intensive pesticide use, which are perceived as simpler and faster solutions for pest control (Zheng and Xu, 2023). Moreover, even farmers familiar with the concept of IPM often face limited institutional and local support, as well as a shortage of experts who could provide adequate professional guidance in applying these measures. Such circumstances further complicate the adoption and broader implementation of IPM, particularly within smaller and less-developed agricultural communities.

Economic Constraints

IPM offers significant long-term economic benefits, such as reduced costs for chemical pesticides and improved soil quality; however, the initial investments required for its implementation can be substantial. Procuring biological agents, introducing pest

monitoring technologies, and educating farmers about modern plant protection methods demand significant financial resources, which poses a particular challenge for small farms (Bajagić et al., 2023). Additionally, limited availability of financial incentives and subsidies for farmers implementing IPM further hinders its wider adoption. In many countries where IPM is not legally mandated, farmers often refrain from its use due to a lack of immediate economic benefits. This problem is particularly pronounced in developing countries, where institutional and financial support for agricultural innovations is often insufficient.

Limitations Due to Technical and Climatic Factors

The implementation of IPM is often associated with substantial technical challenges, especially in regions characterized by unfavorable climatic conditions or significant fluctuations in pest populations. In areas with extremely high temperatures and increased humidity, such as tropical and subtropical zones, the effectiveness of biological measures can be limited due to accelerated insect reproduction or insufficient natural enemy populations. These conditions require the development and application of tailored strategies involving intensified monitoring and flexible adaptation of pest control methods (Bajagić and Ignjatović, 2025). Furthermore, many IPM measures depend on continuous monitoring of crop conditions, which represents an additional burden for farmers lacking access to modern technological solutions for tracking pest populations and climatic parameters. These factors can significantly reduce the accessibility and applicability of IPM for small-scale producers, as well as in remote and less-infrastructurally developed rural areas.

Limited Availability of Biological Agents

Biological control is one of the core pillars of IPM; however, the availability of biological agents, such as natural predators or parasitoids, is often limited. In many regions, farmers do not have easy access to commercially available natural enemies of pests, which are essential for effective population management. The lack of these resources can increase reliance on chemical pesticides, reducing IPM's potential to provide sustainable pest control (Galli et al., 2024).

Limitations Due to Incomplete Legal and Regulatory Support

Although many countries, including Serbia and EU member states, have legislative frameworks that encourage IPM adoption, regulatory challenges remain regarding the quality control of biological agents and the effectiveness of IPM measures. In certain countries, the regulatory system is underdeveloped, or adequate mechanisms to control the quality of biological products available on the market do not exist. The limitations of IPM are complex and include insufficient farmer education, high initial costs, technical challenges, and limited availability of biological agents. Overcoming these difficulties requires improving education, increasing access to financial incentives, and developing new technologies and methods that will enable wider and more effective implementation of IPM across diverse agro-ecological conditions.

CONCLUSION

Integrated Pest Management represents a systematic, multidisciplinary, and environmentally responsible approach to crop protection, providing a balance between productivity, economic efficiency, and environmental conservation. Although its implementation requires a high level of expertise, continuous monitoring, and effective coordination, the benefits of IPM, including reduced reliance on chemical pesticides, preservation of biodiversity, and long-term sustainability, make it a critical component of modern agriculture, especially under the pressures of climate change. From a scientific perspective, future research should focus on the development of innovative IPM methods, incorporating digital technologies, precision agriculture, biological, and agroecological strategies, with the aim of optimizing effectiveness while minimizing ecological and economic costs.

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EVALUATION OF WHEAT GENOTYPE STABILITY THROUGH GGE BIPLOT ANALYSIS

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Abstract: Under pronounced climate changes, identifying wheat genotypes with high yield potential and high stability across environments is becoming essential. A multi-environment trial (MET) with 15 wheat genotypes was conducted across three localities (Pančevo, Kragujevac, and Kruševac) during two growing seasons (2022/2023 and 2023/2024). The study evaluated genotype stability and adaptability for the number of grains per spike and assessed the discriminatory power of the test environments. The GGE biplot presented the combined genotype (G) + genotype × environment (GE) effects, with PC1 and PC2 explaining 58.88 and 19.98% of the total variation, respectively. The spelt wheat lines achieved the highest values for the number of grains per spike and were positioned closest to the “ideal genotype”. Among the bread wheat genotypes, the line KG-40/1 showed the highest value and was narrowly adapted to the environmental conditions of Pančevo and Kragujevac in 2022/2023 season. The genotypes KG-9/1, KG-43/1, and NS 40S demonstrated high stability and high numbers of grains per spike. Environment Pančevo 2023/2024 exhibited the greatest representativeness and discriminative ability, making it the most suitable for genotype evaluation. These findings provide a practical basis for selecting stable and well-adapted genotypes in future wheat breeding programs.

Keywords: Multi-environment trial (MET), Adaptability, Stability, G × E interaction.

INTRODUCTION

Wheat (*Triticum aestivum* L.) is a fundamental staple food, with global production reaching approximately 799 million tonnes in 2023, obtained from over 220 million hectares of harvested area and an average yield of about 3.6 t ha⁻¹ (FAOSTAT, 2025). Wheat, as an important part of the human diet, provides about 18% of global calories and 19% of total protein, highlighting its key role in food security (Erenstein et al., 2022). Global population growth from 7.7 billion to around 9.7 billion by 2050, eventually reaching 10.3 billion in the mid-2080s (UN-DESA, 2024), could increase annual wheat demand by about 132 million tonnes, assuming per capita consumption remains constant (Erenstein et al., 2022). Drought stress is a major abiotic factor affecting wheat growth and yield. Xu et al. (2023) established that drought stress conditions reduced wheat grain yield by over 30%. If such trends in severe drought continue, wheat production may decline further, threatening global food and nutritional security (Mansour et al., 2020). The phenotypic expression of wheat yield components and grain yield depends on the genotype, environment, and the genotype-

by-environment interaction (GEI) (Begna, 2020; Bratković et al., 2024). Therefore, understanding GEI is crucial for developing high-yielding wheat varieties that perform consistently across diverse environments (Begna, 2020). To evaluate crop performance under varying environmental conditions, multi-environment trials (METs) are of crucial importance (Taherian et al., 2024; Mullalem et al., 2024). The genotype plus genotype-by-environment (GGE) biplot method is widely applied for analyzing genotype stability and identification of ideal environments for testing genotypes (Omrani et al., 2022).

The aim of this study was to: (I) evaluate the stability and adaptability of the analyzed wheat genotypes for grain number per spike using GGE biplot analysis; and (II) identify the most suitable environment for genotype testing.

MATERIAL AND METHODS

Plant Material and Experimental Design

The study included 15 wheat genotypes: 10 promising KG bread wheat lines (*Triticum aestivum* ssp. *vulgare*) (KG-4/1, KG-9/1, KG-11/1, KG-16/1, KG-21/1, KG-30/1, KG-33/1, KG-40/1, KG-41/1, and KG-43/1) developed at the Centre for Small Grains and Rural Development in Kragujevac, and three bread wheat varieties used as standards: NS 40S, Renesansa, and Pobeda, originating from the Institute of Field and Vegetable Crops in Novi Sad. In addition, two KG spelt wheat lines (*Triticum spelta* ssp.), KG-54-7/3-5 and KG-54-7/3-2, were included to broaden the variability of the analyzed germplasm and to assess their yield potential across different environments. The field experiment was carried out at three localities: Pančevo (Experimental Field of the “Tamiš” Research and Development Institute, 44°56'31" N, 20°43'18" E, 80 m), Kragujevac (Experimental Field of the Center for Small Grains and Rural Development, 44°02'47" N, 20°56'54" E, 196 m), and Kruševac (Experimental Field of the Institute for Forage Crops Kruševac, 43°34'56" N, 21°12'16" E, 148 m), across two growing seasons (2022/2023 and 2023/2024). At all localities, the wheat genotypes were arranged in a randomized complete block design (RCBD) with three replications, and the plot size was 5 m². Standard agronomic practices for wheat production were applied. In the first season, sowing was performed on October 26, 2022, in Pančevo, November 4, 2022, in Kruševac, and November 9, 2022, in Kragujevac. In the second season, sowing was performed somewhat later at all localities: November 2, 2023, in Pančevo, November 14, 2023, in Kruševac, and November 20, 2023, in Kragujevac. Harvest was carried out in both seasons when grain moisture fell below 14%. In the first season, the harvest dates were July 13 in Pančevo, July 18 in Kragujevac, and July 12, 2023, in Kruševac. The second season was characterized by an earlier harvest in all localities. Thus, the harvest in Pančevo was carried out on June 26, 2024, in Kragujevac on July 10, 2024, and in Kruševac on July 4, 2024.

At full maturity (BBCH 89), samples were collected for the analysis of grain number per spike. From each plot, 10 plants were randomly selected (30 plants per genotype across three replications), and the number of grains per spike was determined by manually counting all grains on the main spike.

Agro-meteorological Conditions

Meteorological data for Pančevo and Kruševac were obtained from stations located at the experimental fields, while data for Kragujevac came from the nearby station of the Republic Hydrometeorological Service of Serbia (www.hidmet.gov.rs/) (Figure 1).

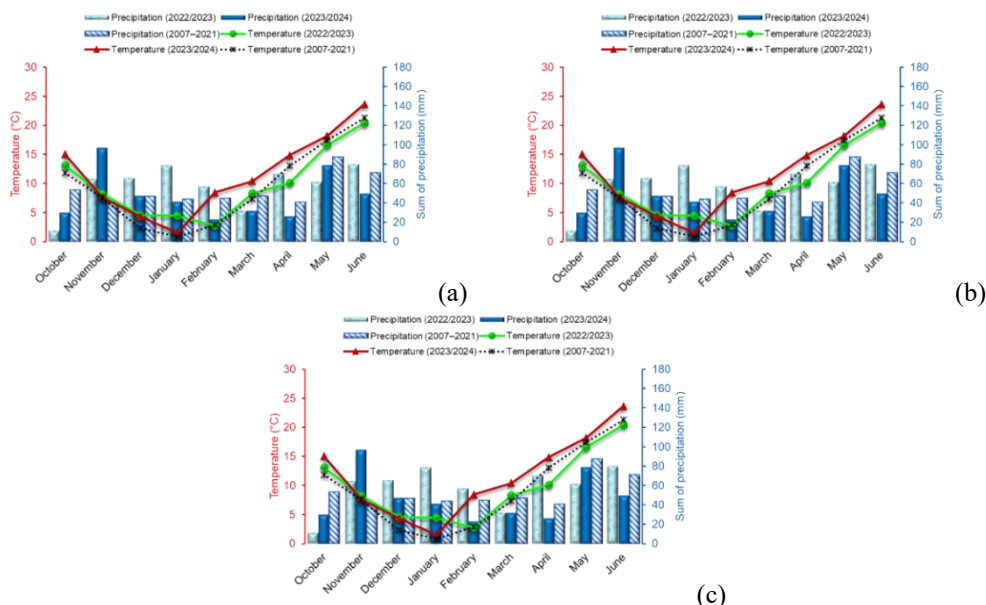


Figure 1. Meteorological conditions during the experiment at three localities: Pančevo (a), Kragujevac (b), and Kruševac (c), during two growing seasons

December-January in both seasons was notably warmer than average. In the first season, precipitation exceeded the average for all localities, whereas in the second season it was below average, prolonging the growth period and delaying dormancy. During the tillering phase (February), temperatures were near average in the first season but extremely high in the second, accompanied by reduced precipitation, particularly in Kragujevac. These conditions accelerated early tillering. During stem elongation and anthesis (March-May) in the first season, Kruševac was characterized by slightly lower temperatures and reduced precipitation, while Pančevo and Kragujevac recorded lower temperatures accompanied by higher precipitation. In April 2024, temperatures were above average at all localities, which contributed to a shortened stem elongation phase. In June of the first growing season, temperatures at all localities were within the multi-year average, while significantly higher precipitation was recorded in Kragujevac and Kruševac (Figure 1).

Statistical Analysis

To identify genotypes with high yield and stable performance across different agroecological environments, as well as to define potential mega-environments, a GGE biplot analysis (Genotype plus Genotype $\times$ Environment interaction) was carried out. The first two principal components were used to generate several biplots, including Mean vs. Stability, Which-Won-Where, Discriminativeness vs. Representativeness, and Genotype Ranking. This analysis was conducted using the metan package (Olivoto and Lúcio, 2020) in R version 4.3.2.

RESULTS AND DISCUSSION

To increase wheat yield, it is not sufficient to improve photosynthesis or grain weight, since increasing grain number or sink strength is a key factor for yield improvement (Slafer et al., 2023; Serrago et al., 2025). Positive correlations between grain number per spike and grain yield in wheat were reported by Philipp et al. (2018). Zečević et al. (2018), studying different spelt wheat genotypes, also noted that grain number per spike is an important component of grain yield and contributes to grain yield potential.

From a plant breeding perspective, it is particularly important to investigate GEI, which arises as a result of changes in genotype ranking or fluctuations in absolute differences among genotypes without changes in ranking (Saeidnia et al., 2017). In order to examine the combined effects of genotype and genotype $\times$ environment interaction, GGE biplot analysis was applied. The first principal component (PC1) explained 58.88% of the total variation, while the second (PC2) accounted for 19.98%, together explaining 78.86% of the variability in the dataset for grain number per spike (Figure 2a). The high proportion of variance explained by the first two principal components indicates a complex GEI in multi-environment trial (MET) data (Mullalem et al., 2024). In the “Mean vs. Stability” biplot (Figure 2a), the AEC axis represents the average performance of genotypes across environments, while the stability of individual genotypes is determined by their distance from this axis, corresponding to their projection onto the AEC ordinate (Yan et al., 2007; Omrani et al., 2022; Taherian et al., 2024). The genotypes of spelt wheat (G14 and G15) had above-average grain number per spike and moderate stability. Among bread wheat genotypes, KG-40/1 (G8), Renesansa (G12), KG-9/1 (G2), and Pobeda (G13) stand out with above-average grain number per spike. Genotype KG-9/1 (G2) was the most stable among the above-average genotypes (Figure 2a).

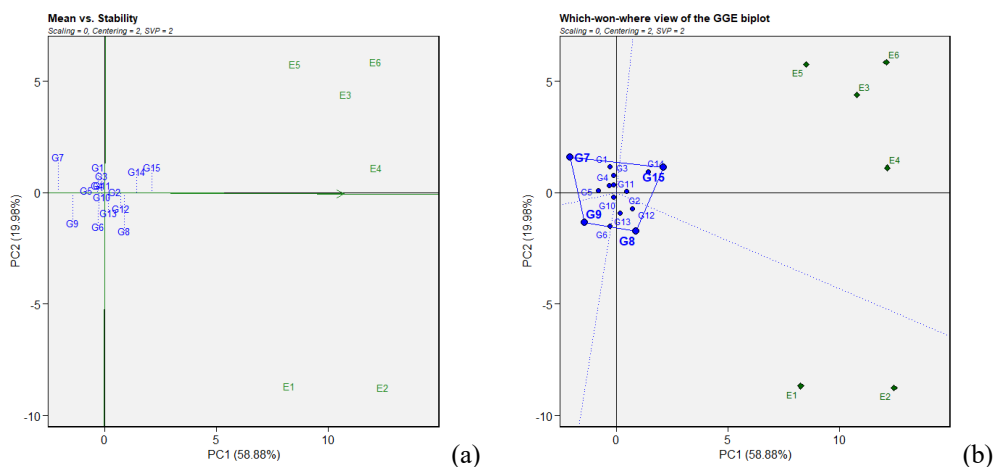


Figure 2. Mean vs. Stability (a) and Which-won-where (b) view of the GGE biplot analysis for number of grains per spike

With the aim of identifying winning genotypes in specific environments, as well as defining mega-environments, a Which-won-where GGE biplot was constructed (Yan et al., 2007), Figure 2b. The genotypes KG-33/1 (G7), KG-41/1 (G9), KG-40/1 (G8), and KG-54-7/3-2 (G15) were positioned farthest from the origin in different directions, forming a polygon. These genotypes are the best or worst in one or more environments (Saeidnia et al., 2023).

A set of perpendicular lines from the origin divided the biplot into sectors. Environments E3 (Kruševac 2022/2023), E4 (Pančevo 2023/2024), E5 (Kragujevac 2023/2024), and E6 (Kruševac 2023/2024) were located within the same sector, forming a mega-environment in which genotype KG-54-7/3-2 (G15) was the winning genotype. Environments E1 (Pančevo 2022/2023) and E2 (Kragujevac 2022/2023) fell into a separate sector, with genotype KG-40/1 (G8) at the vertex, suggesting its specific adaptation to these environments. Genotypes G7 (KG-33/1) and G9 (KG-41/1), positioned at the polygon vertices but within sectors that did not include any environment, were characterized by a low grain number per spike at the trial level. Genotypes KG-9/1 (G2), KG-16/1 (G4), NS 40S (G11) and Pobeda (G13), located closer to the center of the biplot, exhibited stable performance for grain number per spike (Figure 2b).

The “Discriminativeness vs. Representativeness” GGE biplot for grain number per spike identifies Kragujevac 2022/2023 (E2), Kruševac 2023/2024 (E6), Pančevo 2022/2023 (E1), and Pančevo 2023/2024 (E4) as the most discriminative environments, as they have the longest vectors (Figure 3a). Yue et al. (2025) emphasized that highly discriminative environments are suitable for identifying stable genotypes with broad adaptability. In contrast, the environment Kragujevac 2023/2024 (E5) shows the lowest discriminative power. Representativeness is evaluated according to the angle between the environment vector and the AEC axis, where a smaller angle indicates greater representativeness (Saeidnia et al., 2023). Accordingly, the most representative environment is Pančevo 2023/2024 (E4), which forms the smallest angle with the AEC axis. The environments Pančevo 2022/2023 and Kragujevac 2022/2023 form the largest angle with the AEC axis, making them the least representative. Based on the obtained results, we conclude that Pančevo 2023/2024 (E4) is the ideal environment for genotype evaluation, as it is both representative (forming a small angle with the AEC axis) and discriminative (having a long vector) (Figure 3a).

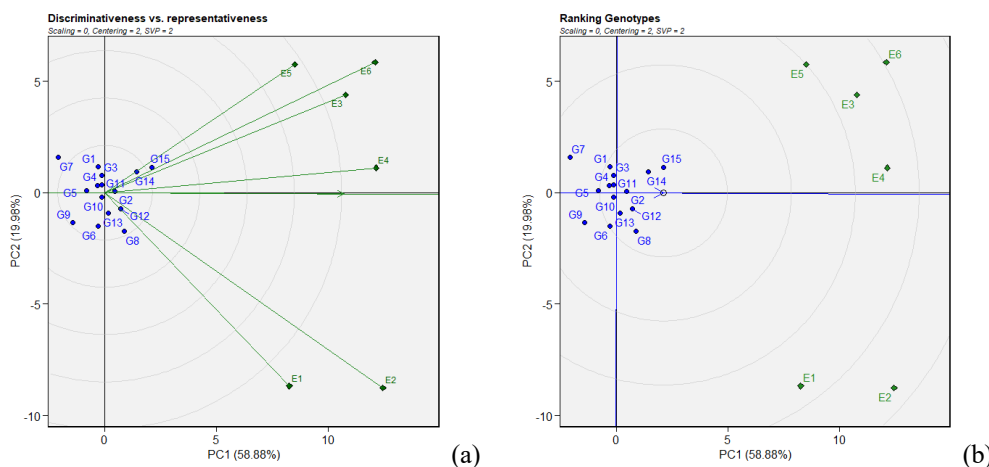


Figure 3. Discriminativeness vs. representativeness (a) and Ranking genotypes (b) view of the GGE biplot analysis for number of grains per spike

A Ranking Genotypes GGE biplot was constructed with the aim of ranking genotypes and identifying the ideal genotype within the evaluated set of genotypes (Figure 3b). The hypothetical “ideal” genotype is represented at the center of the concentric circles, in the direction of the blue arrow. The spelt lines KG-54-7/3-5 (G14) and KG-54-7/3-5 (G15) are positioned closest to the ideal genotype, demonstrated a high value for the examined trait as

well as high stability at the trial level. Also located near the ideal genotype the bread wheat genotypes KG-9/1 (G2) and Renesansa (G12). Using this type of GGE biplot, Bishwas et al. (2021) identified an ideal elite wheat line that can be used as a reference for evaluating other lines.

CONCLUSION

Spelt genotypes stood out with the highest values of grain number per spike and moderate stability. Line KG-9/1 showed the highest stability among the above-average genotypes. Two mega-environments were identified, with genotype KG-40/1 winning in the environments of Pančevo and Kragujevac in the 2022/2023 season, while the spelt line KG-54-7/3-2 showed specific adaptability under the conditions of Pančevo and Kragujevac in 2023/2024, and Kruševac in both seasons. Genotypes KG-33/1 and KG-41/1 were characterized by the lowest trait values and pronounced instability. Pančevo 2023/2024 was identified as the ideal environment for genotype evaluation, characterized by high discriminativeness and representativeness.

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EM BIOTECHNOLOGY - THE FUTURE IN SUSTAINABLE AGRICULTURAL PRODUCTION

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Abstract: Due to environmental degradation environment, the consequences of climate change, and the need to produce food with high nutritional value, there is an increasing number of research whose results highlight the importance of applying a large group of microorganisms known as effective microorganisms or EM biotechnology. Biopreparations containing EM are widely used in sustainable agriculture. This versatile potential for using effective microorganisms results from their high enzymatic specificity, which enables them to survive in different environments. EM do not have a withdrawal period, making them suitable for use in sustainable agricultural production systems. The use of EM preparations has been intensive worldwide since the 1980s. In Serbia, research is being conducted on the application of biopreparations with EM in sustainable agricultural production systems in both farming and vegetable growing. The aim of the research is to highlight the importance of introducing this group of microorganisms into integrated wheat production. Wheat is one of the most important plant species in human nutrition. This paper presents the results of the impact of applying biological preparations with EM on soil biogenicity parameters in the rhizosphere and the productive properties of different wheat varieties. Based on the presented results, it can be concluded that EM biotechnology is a safe way to fulfill the principles of sustainable agricultural production in this case of wheat.

Keywords: Effective EM microorganisms, Sustainable agriculture, Wheat

INTRODUCTION

Management strategies in sustainable agricultural systems aim to reduce the input of chemical fertilizers, pesticides and energy demand in general, the main goal of which is to protect the environment and reduce the impact on climate change. In systems of sustainable agricultural production, it is necessary to apply diversified crop rotations, integration of livestock and crop production, a greater share of legumes such as seed crops, intercrops or intercrops in rotation, organic fertilization and integrated pest and disease management. Knowing that natural resources are limited, it is necessary to develop sustainable methods of food production to ensure food security for an ever-growing population (Gabardo et al., 2020; Macoski et al., 2021; Clock et al., 2021). Microbes have a significant place in sustainable methods aimed at promoting environmental protection, agricultural

biotechnology and more efficient treatment of agricultural and municipal waste. In order to stimulate natural biological cycles (cycles of biogenic elements) in practice, as a mandatory measure, different groups of microbes are used as biofertilizer.

The group of biofertilizers includes microbes that have the ability to fix elemental nitrogen (*Rhizobium*, *Azotobacteraceae*), then those that release phosphorus (*Bacillus megaterium* *vr. phosphaticus*) and potassium (*Bacillus circulans*) into the soil from organic matter, making these elements available to plants, and groups of microbes that prevent the development of phytopathogenic microorganisms (Bolińska et al., 2005, 2008).

In the modern directions of agricultural production, the most important role is played by inoculants with microbes that can be used as biofertilizers, biostimulators and biopesticides. In this sense, a new concept is emerging EM biotechnology with effective microorganisms (EM).

Effective microorganisms are mixed cultures consisting of photosynthetic bacteria, lactic acid bacteria, yeasts, actinomycetes and fermentation fungi. The concept of EM biotechnology was developed by Professor Thibault Higa in the 1980s as a need to reduce organic waste in the environment and protect the soil (Higa, 1994). These microbes are classified into large functional groups such as: photosynthetic bacteria, lactic acid bacteria, yeast group, actinomycete group and fungi. This technology is part of the National Program in 140 countries in the world, where they have proven to be the most appropriate way to replace traditional measures in plant nutrition and protection and improving soil quality. Thanks to EM biotechnology, farmers around the world can increase the quantity and quality of crops without impacting the environment (Paśmionka et al., 2015; Vaitkevičienė et al., 2021; Bajagić et al., 2024). Interest in the use of EM in agricultural practices has grown significantly in recent years both in promoting plant growth and in the biological control of plant pests and diseases. They also represent potential substitutes for chemical products and therefore can contribute to the preservation of the environment (Domenico, 2019). They have found their application in areas of agriculture such as soil regeneration, crop production, livestock production, agri-food industry and storage. Such a versatile potential of using effective microorganisms is a consequence of the high enzymatic specificity of microorganisms, which allows them to survive in different environments. The use of EM biotechnology in farming meets Global GAP standards, preserves soil quality and respects the principles of economy and ecology that are part of the EU National Program for Sustainable Development.

Concerns about environmental problems, climate change created by agricultural production processes, are increasing the need for research that will indicate the real benefits of EM for plants and soil (Golec et al., 2007; Mayer et al., 2010). The lower efficiency of chemical products, the greater occurrence of resistant diseases and pests, and the rising costs of production have driven the market for biological inputs (De Melo et al., 2021). New research results are always needed and have helped improve production, formulation, storage and field application techniques, both small and large scale. The use of preparations with EM has long been tested in Japan, China, Malaysia, Russia, Poland, the Czech Republic, Romania, while the biggest user of preparations from EM biotechnology is Brazil, where effective microorganisms have proven to be the most suitable way to replace traditional management methods with natural methods. They have found application in the

form of intercrop spraying, after harvest residues, manure mineralization, for the treatment of seeds, tubers and rhizomes, and directly or foliarly on plants (Pszczółkowski et al., 2018; Wu et al., 2013; Cvijanović et al., 2024). Significant production effects are also observed when using preparations with EM for the preparation of high-quality fertilizers, compost and plant extracts as strong nutrients (Huk, 2009).

Advantages of Applying EM Biotechnology in Plant Production

Effective microorganisms play a major role in the preparation of manure. Manure is a mixture of substances of organic origin from plants and animals. In its fresh state, it is not important for use but must be subjected to the fermentation process. Adding EM directly to the manure prevents the spread of unpleasant odors of ammonia and trimethylamine, which are produced in the fermentation process, and reduces the presence of harmful insects. Gunawan et al. (2020) determined that the application of EM in the preparation of poultry manure can reduce the ripening time by 21 days, and that it affects the increase in the morphological characteristics of amaranth (*Amaranthus hybridus*). Hamad et al. (2020) showed that adding preparations with EM in a concentration of 1% reduces the growth of pathogenic bacteria (*S. aureus* and *E. coli*). Safwat et al. (2018) determined that in the presence of EM in a concentration of 0.5-1%, the growth of pathogenic bacteria such as *Bacillus subtilis*, *Neisseria gonorrhoeae*, *Pseudomonas aeruginosa*, *Streptococcus faecalis*, *Aspergillus flavus*, *Aspergillus niger*, *Candida albicans* and *Candida parapsilosis*. The primary role of EM in inhibiting the growth of pathogenic bacteria has not been precisely determined, but it is assumed to arise as a result of competition in the food medium with pathogenic organisms. Then the products of EM metabolism such as lactic acid act as sterilizers that inhibit harmful microbes (Vicente et al., 2007; Safwat et al., 2018). Reddy and Giller (2008) found that adding EM in squash and legume production can successfully control insects. The application of EM by spraying plants over the leaves several times during the growing season affects the increase in the nutritional properties of the fruits of lettuce, corn, wheat, and soybean plants (Stojanović et al., 2020; Stepić et al., 2022; Cvijanović et al., 2022a). Effective microorganisms are important in composting organic waste. Bastami et al. (2016) determined that during composting of organic waste at the beginning of the process, the temperature and the content of macronutrients NPK increase in the pile, which indicates a faster activity of total microbes. Gases such as methane, nitrogen and carbon oxides are released during these processes. The results of Joung-Soo's research (2015) showed that by adding EM to the composting mixture, the ammonia removal efficiency was 55.9%, which is very important from the aspect of reducing the production of greenhouse gases.

Considering the necessity of development and expansion of food production according to the principles of sustainable production, EM biotechnology offers the possibility of developing ecological methods of growing plants.

For the last few years, research has been conducted on the effect of applying EM biotechnology preparations in plant production in agroecological conditions in Serbia. The aim of the work is to point out the importance of the introduction of this group of microbes in the production of wheat, which is one of the most important plant species in human nutrition.

MATERIAL AND METHODS

The paper will present the results of the three-year research on the location of Padinska Skela (YN 44° 56', λE 25° 28') region Banat. The area of the experimental plot was 576 m², and the elementary plot was 5 m². The plots were laid out according to the plan of divided plots in four repetitions. The first crop was corn. All agrotechnical measures were applied in optimal terms. In the experiment, a liquid preparation with effective microorganisms EM Aktiv (trade name) was used (Figure 1). The preparation is registered and certified for organic production in Serbia and the EU. On the website of the Ministry of Agriculture, Water Management and Forestry of the RS, the preparation EM Aktiv is on the list of permitted and registered means for plant nutrition and soil improvers that can be used in organic agriculture (www.minpolj.gov.rs/organska/).



Figure 1. Application of preparations with EM in the foliar wheat crop

Different varieties of wheat (domestic and foreign) were used for sowing. Microbiological methods were used to determine the basic parameters of soil biogenicity (total number of microorganisms and abundance of azotobacter) in the rhizosphere of wheat varieties Talas, Simonida, NS-40 and Sirtaki. The total number of microorganisms was determined on soil agar dilution 10⁻⁷, and the number of azotobacter on Fyodor's medium by the method of fertile drops dilution 10⁻¹. Generative properties, weight of 1000 grains and yield, were determined in Ratarica, Pobeda, Nogal and Apache varieties. The characteristics of the soil are given in Table 1. The soil is slightly alkaline in KCl to slightly alkaline reaction in H₂O. According to the content of CaCO₃, it belongs to the low carbonate group. Medium is provided in humus, and the content of phosphorus and potassium is higher than the optimal values (15-20 mg/100 g optimal for agricultural production).

Table 1. Agrochemical properties of soil on experimental plots

pH		CaCO ₃ (%)	Hummus (%)	Total inorganic nitrogen mg /kg	P ₂ O ₅ mg/100 g	K ₂ O mg/100 g
KCl	H ₂ O					
6.23	7.60	1.07	2.33	6.98	21.45	34.58

RESULTS AND DISCUSSION

The foundation that maintains the food chain is the soil in which different types of microbes live. Based on this concept, it was determined that the use of EM contributes to the natural strengthening of the productive capacity of the soil. Souza et al. (2015) state that EM biotechnology can be used successfully in soil revitalization, because they "clean" it from

various toxicants and make the soil richer in vital energy. By applying beneficial microorganisms, the soil retains more water, which means more successful plant production in periods of drought or when growing on sandy soil. This improvement is a consequence of the increase of organic matter in the soil, the reduction of porosity, due to microbial activity, and the ionic balance, which favors the interaction of surface charges of the physical structure of the soil with ionic charges (Hoyos et al., 2008). When they are introduced into the soil, directly or through seeds, they have a positive effect on increasing the microbial biodiversity in the soil, whereby the nutrients from the soil become more quickly available to the plants, because they accelerate the mineralization processes of organic matter. Microbial preparations with EM, in addition to living cells of different groups of microbes, contain amino and humic acids, vitamins, hormones, enzymes and antibiotics that are the result of metabolic processes of the microbes themselves.

On the plot where soil biogenicity parameters were determined, basic fertilization with complex NPK fertilizer in the amount of 400 kg ha⁻¹ (15:15:15) was applied in the autumn before sowing. In the spring, supplementary fertilization was carried out with organic pelleted poultry manure in the amount of 1750 kg ha⁻¹ (4:4:4) (F₁). Poultry manure was treated with a biopreparation that was diluted with water in a ratio of 1:10 (F₂). In the control variety (F₀), top dressing was with 150 kg ha⁻¹ Urea (46 N%). The basic indicators of the condition of the soil, the total number of microorganisms (TNM) and the abundance of azotobacter (Az) in the rhizosphere of wheat in the earing phenophase, were monitored. According to Mićanović (1997), in the rhizosphere of wheat, depending on the genotype of the plants, the largest number of microorganisms was found in the wheat heading stage. The total number of microorganisms in the soil has long been taken as a reliable indicator when assessing the condition of the soil. The abundance and composition of the total microflora is higher in soils with a higher content of organic matter and optimal agrochemical properties. The tested varieties had a high influence on the variability of the total number of microorganisms in the soil, and the differences obtained were statistically very significant. A greater number of total microflora is not an indicator of a greater effective production capacity of the soil, because it depends on a number of other factors, but it certainly represents a greater potential for the formation of organic matter in the soil. The efficiency of applied EM was statistically highly significant (Table 2). The total number of microorganisms in the F₂ variant was 75.26% higher than in the F₁ variant and 139.47% higher than in the F₀ control. The results indicate that the autochthonous microbial population has been activated. It is assumed that there was a competition for food of introduced EM microorganisms with the autochthonous population in the rhizosphere microbiome, but also that there was a greater production of substances of microbiological origin that can be food for different types of microbes.

Table 2. The total number microorganisms in the rhizosphere of tested wheat varieties depending on the method of fertilization CFU ml⁻⁷ g⁻¹ of absolutely dry soil

Variety (A)	Fertility B			□A	Factor	LSD	
	F ₀	F ₁	F ₂			5%	1%
Talas	34.52	66.94	70.61	57.35			
Simonida	37.84	60.56	86.65	61.68	A**	1.39	1.89
NS 40S	28.01	60.63	88.53	59.05	B**	4.20	6.63
Sirtaki	37.44	53.37	84.24	58.35	A x B**	12.40	13.27
□ B	34.45	60.38	82.50	59.11		CV (%) = 2.33	

Azotobacter is a very important group of bacteria that fix atmospheric nitrogen and translate it into forms available to plants. This group of bacteria is very sensitive to all changes that occur in the soil and reacts with its abundance and life activity. Okon and Kapulnik (1986) determined that some species of *Azotobacter* can be found on the roots of wheat in the early stages of development, even in the tissue of the roots of wheat at the site of formation of the knot of bokorenia. That is why it is very important to apply methods that increase the number and activity of this group of bacteria. The variability of the number of *Azotobacter* was highly significant in varieties, in the application of fertilizers and in the relationship between these two factors. A statistically significant increase in *Azotobacter* was determined by EM application from 21.78% compared to the control, to 5.44% compared to the variant without EM application (Table 3).

Table 3. The abundance *Azotobacter* in the rhizosphere of tested wheat varieties depending on the method of fertilization CFU ml⁻¹ g⁻¹ of absolutely dry soil

Variety (A)	Fertility B			□ A	Factor	LSD	
	F ₀	F ₁	F ₂			5%	1%
Talas	113.6	151.6	173.7	146.3			
Simonida	142.9	157.7	167.3	162.5	A**	3.75	5.10
NS 40S	116.6	133.3	123.8	124.6	B**	3.25	4.41
Sirtaki	89.26	91.4	98.26	92.98	A x B**	6.50	8.83
□ B	115.59	133.50	140.77	129.95	CV (%) = 2.89		

In the second part of the experiment, where the varieties Ratarica, Pobeda, Nogal and Apache were grown, EM was applied twice during the growing season (in the phenophase of budding and before earing). Fertilization with 400 kg ha⁻¹ NPK (15:15:15) before sowing in autumn was carried out as a source of nutrients for the plants. In the spring, during the budding phenophase, top dressing with urea (46%) was carried out, namely 150 kg ha⁻¹ (N₀), 150 kg ha⁻¹ (N₁) and 100 kg ha⁻¹ (N₃). In variants N₂ and N₃, EM was foliarly applied in the amount of 6 l ha⁻¹. The productive properties of plants with a weight of 1000 grains and grain yield were determined. In wheat production, it is very important to achieve a large weight of 1000 grains. If the weight of 1000 grains are greater, the germination, budding, longer ears and yield are higher. With an increase in the weight of 1000 grains, the resistance of the variety to unfavorable agrometeorological conditions increases, and the quality of grinding wheat grains is better. Using EM, a significant increase in the weight of 1.000 grains (p<0.05) was determined compared to the control and the variant in which the amount of urea was reduced. However, no statistically significant difference was found between the control N₀ and the variant N₂. The weight of 1000 grains were higher than the control by 1.83% and compared to the N₂ variant by 1.68% (Table 4).

Table 4. The influence of EM on the weight of 1000 grains (g)

Variety (A)	Fertility B			□ A	Factor	LSD	
	N ₀	N ₁	N ₂			5%	1%
Ratarica	41.65	41.17	41.87	41.56			
Pobeda	43.18	44.10	43.58	43.62	A**	1.13	1.72
Nogal	37.43	38.99	38.58	38.33	B*	0.50	1.07
Apač	39.04	40.04	39.53	39.53	A x B*	1.20	1.56
□ B	40.33	41.07	40.39	40.76	CV (%) = 7.99		

The obtained results are compatible with the results of Jalil et al. (2017) who show that it is possible, depending on the characteristics of the variety, to reduce the amount of mineral nitrogen by using biopreparations with effective microorganisms. Different types of microorganisms that make up EM produce different substances such as: organic acids, plant hormones (gibberellins, auxins and cytokinins), vitamins, antibiotics and polysaccharides. All these substances directly or indirectly have a positive effect on plant growth. They improve the photosynthetic capacity, applied foliar has the effect of supplementary fertilization, and eliminate the use of pesticides and increases the resistance of plants to oxidative stress, which has a positive effect on grain yield. According to the research conducted, it was determined that the yield increase in the N1 variant ranged from 6.84% (N₀) to 2.43% (N₂), which was at the level of ($p < 0.01$) (Table 5).

Table 5. Yield of wheat grain (kg ha⁻¹)

Variety (A)	Fertility B			□ A	Factor	LSD	
	N ₀	N ₁	N ₂			5%	1%
Ratarica	6.220	6.447	6.534	6.400			
Pobeda	6.340	6.852	6.452	6.548	A*	0.66	0.96
Nogal	5.877	6.241	5.957	6.025	B*	0.23	0.36
Apač	6.269	6.857	6.826	6.650	A x B	0.44	0.64
□B	6.176	6.599	6.442	6.405,7	CV (%) = 11.47		

With the use of microbiological agents as growth stimulators and agents in the biological control of diseases and pests in crops, we are in a new era of food production. EM biotechnology can contribute to intensive use, especially in sustainable production systems as well as in drought conditions. During the implementation of biocontrol measures and/or promotion of plant growth, favoring the preservation of the environment, they have been identified as a viable alternative for ecologically and economically sustainable systems of agricultural production. Knowing all the benefits of EM for plants, research is needed to demonstrate its effectiveness in different ways of application and in different agroecological conditions.

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WOMEN'S EDUCATION AND ECONOMIC INCLUSION IN BRICS+: TREND ANALYSIS 1991-2022

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Abstract: This paper analyses the position of women in BRICS+ member countries through the prism of education and their integration into the labour market in the period 1991-2022, using World Bank data (2024). The research focuses on the interrelationship between these parameters, viewing education as the foundation of social mobility and economic progress, gender equality as a precondition for sustainable social development, and women's participation in the labour market as an indicator of the actual level of integration and economic inclusion. By applying descriptive and comparative analysis, different trends in the gender gap are identified, indicating that higher participation of women in education is associated with a higher level of their economic inclusion. The aim of the paper is to highlight the importance of education and the equal inclusion of women in economic activity, as well as the potential that these processes have for improving social cohesion and long-term economic growth within the BRICS+ group. The results show that the development of institutional mechanisms to support women in the labour market is necessary and confirm that gender equality is a key precondition for sustainable economic development and social stability within BRICS+.

Keywords: BRICS+, Women, Education, Labour market, Inclusion

INTRODUCTION

Although BRICS was not initially focused on social and gender issues, in recent years the importance of gender equality for sustainable development and stable economic growth has been increasingly recognized (UNDP, 2023; Dugarova, 2019). In this context, the role of women as agents of change has gained more space in strategic documents, forums and initiatives of BRICS and the expanded BRICS+.

Women make up a significant part of the working-age population, but their position in the economy is often precarious, due to limited access to leadership positions, entrepreneurial resources and financial instruments (ILO, 2021). In addition, unpaid domestic and care work, which is largely performed by women, further reduces their scope for economic empowerment (Kabeer, 2012).

Although member states have adopted numerous laws and strategies aimed at reducing the gender gap and improving the position of women in the labour market, the effects of these measures often remain limited due to deep-rooted socio-economic and cultural barriers

(OECD, 2020). At the same time, women in BRICS+ countries are increasingly entering the spheres of innovation, entrepreneurship and public policy, thereby contributing to the construction of a more inclusive and sustainable economic model.

However, in all these countries there is still a clear contradiction between the increasing participation of women in education and public policies, and the persistent inequality in the economic sphere. The key problem remains the invisibility of unpaid domestic work and the limited participation of women in the formal labour market.

Increasing the rate of female labour force participation is not only a matter of social justice but also an economic imperative, especially in the context of ageing populations and declining birth rates in BRICS+ countries (Barro and Sala-i-Martin, 2004).

Taken as a whole, it can be concluded that gender equality is one of the key drivers of sustainable development. Starting from these circumstances, the aim of this paper is to analyse the position of women in BRICS+ countries through the prism of education and their integration into the labour market, examining the trends and challenges that shape the gender gap in the period 1991-2022. The paper seeks to underline the importance of systemic support for women in education and employment as a precondition for accelerated economic growth and the strengthening of social cohesion within the BRICS+ group.

RESEARCH METHODS AND DATA SOURCES

The paper applies both qualitative and quantitative research methods. The qualitative analysis is based on a structured review and interpretation of relevant scientific literature, policy documents and official reports related to education, gender equality and the position of women in the labour market in BRICS+ countries.

The quantitative part of the research is based exclusively on secondary data for the period 1991-2022, obtained from the World Bank World Development Indicators database (2024), complemented by selected aggregated data from national statistical offices. The analyzed indicators reflect key dimensions of women's educational attainment and economic inclusion, including female literacy rates, completion of primary, secondary and tertiary education, labour force participation rates, employment-to-population ratios and female unemployment rates.

The research employs methods of descriptive statistics, focusing on the presentation and interpretation of long-term trends in the selected indicators, as well as comparative analysis, enabling cross-country comparisons within the BRICS+ group. The results are presented graphically to facilitate clearer interpretation of structural differences and dynamics over time. Due to incomplete time-series coverage for certain indicators across countries, graphical analysis was complemented and partially replaced by a structured descriptive comparison, summarized in Table 1.

No primary data collection, such as surveys or questionnaires, was conducted. The analysis relies entirely on official aggregated secondary statistical sources, ensuring consistency, international comparability and methodological transparency.

RESULTS AND DISCUSSION

Over the past decades, women in Brazil have been achieving higher levels of education than men, as reflected in the higher number of female graduates and high rates of female participation in secondary and higher education. Despite this educational progress, economic equality remains a challenge, as women are under-represented in the formal labour market, more often engaged in the informal sector and, on average, paid less than men for the same or similar jobs.

Already at the beginning of the 20th century, the Soviet Union provided women with access to education, employment and the right to vote, which led to a strong inclusion of women in economic activity. Today, Russia has a relatively balanced policy in the areas of health, education and employment.

Over the past ten years, India has been implementing intensive measures to empower and support women, particularly through education and employment in modern sectors such as information technology and entrepreneurship.

China, as the world's second-largest economy, has systematically improved the status of women through policies focused on health, education and the workforce. The result is a high level of female participation in the economy and in public policy.

Since the end of apartheid, South African women have become more visible in political and public life, and their participation in science and technology has increased. However, economic aspects of equality lag behind: women of lower socio-economic status continue to face limited access to resources and the labour market.

The new BRICS members are also gradually changing their social structures towards greater inclusion of women. With its Vision 2030 strategy, Saudi Arabia has doubled the number of women in the workforce and introduced the principle of equal pay (Government of Saudi Arabia, 2016). Egypt, through its National Strategy for the Empowerment of Egyptian Women 2030 (National Council for Women Egypt, 2017), is investing in education and microfinance programmes, while the UAE records high levels of female participation in higher education and public institutions (UAE Gender Balance Council, 2020). Despite formal restrictions, Iran and Ethiopia have seen notable progress in women's education and activism, although their participation in the economy is still predominantly concentrated in informal sectors.

Taken as a whole, it can be concluded that gender equality is one of the key drivers of sustainable development. Systemic support for women in education, health, entrepreneurship and public policy can significantly accelerate economic growth and strengthen social cohesion within the BRICS+ group.

Women's Education - the Foundation of Economics Inclusion

Education is the foundation of economic and social development, as it directly affects women's opportunities to be included in formal economic activity, to reduce poverty and to create high-quality human capital. World Bank data (2024) for BRICS+ countries in the

period 1991-2022 show that women’s literacy rates and completion of different levels of education are strongly correlated with their position in the labour market.

In order to analyze long-term trends in basic educational inclusion, Figure 1 presents the female literacy rate (population aged 15 and above) in BRICS+ countries over the period 1991-2022.

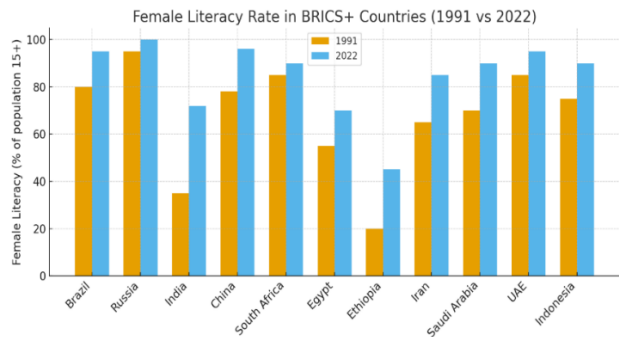


Figure 1. Female literacy rate in BRICS+ countries, 1991-2022.
Source: World Bank, World Development Indicators (2024)

As shown in Figure 1, female literacy (15+) in the BRICS+ group shows a clear polarization. Russia and China have near-universal literacy (99-100%), reflecting long-standing institutional support and equitable access to schooling. Brazil has recorded significant growth – from around 87% in the early 2000s to over 95% in 2022. In contrast, India and Ethiopia continue to lag behind: India, despite rising from around 34% to around 69%, faces marked regional and gender inequalities, while Ethiopia has advanced from less than 20% to around 40-45%, which still indicates a very low level of educational inclusion. South Africa and Egypt are in the middle range (around 70-90%), while Saudi Arabia and the UAE, under the influence of modernization reforms, have reached female literacy levels above 90%. A similar stratification pattern is observed when analyzing women’s educational attainment beyond basic literacy, particularly at primary and lower secondary levels.

When viewed through the share of women aged 25 and over with at least primary and lower secondary education, an even clearer stratification is observed. Russia almost completely achieves universal coverage of primary education (around 100%) and very high coverage of lower secondary education (over 98%). Brazil and South Africa show continued growth, from around two-thirds of the population at the beginning of the 2000s to over 85% in the last decade, which can be attributed to public policies and social programmes aimed at reducing the educational gap. India and Indonesia remain at lower levels (30-50% for lower secondary), indicating persistent barriers to girls’ access to education, particularly in rural areas. Middle Eastern countries (Egypt, Iran, Saudi Arabia, UAE) record dynamic trends, with accelerated growth in the last decade.

In upper secondary and tertiary education, the differences are even more pronounced. Russia maintains a leading position with over 90% of women having completed upper secondary education and over 50% with tertiary education. Brazil and South Africa have seen strong increases in upper secondary completion rates (to around 56% and over 60%,

respectively), while Saudi Arabia and the UAE, influenced by development strategies and growing investment in female education, have reached over 70% for upper secondary and over 50% for tertiary education (in the case of the UAE). Egypt and Iran are progressing more moderately, while India, Indonesia and especially Ethiopia remain at relatively low levels, with Ethiopia recording a negligible share of women with tertiary education (below 1%).

Overall, the educational indicators suggest that higher levels of women’s education are strongly linked to their economic position. Countries with the highest levels of secondary and higher education completion among women (Russia, the UAE, and, to some extent, China and Brazil) simultaneously record more stable female employment rates and a smaller gender gap in the economic sphere. In contrast, in countries where women’s access to education is limited (Ethiopia, India, and partly Indonesia), women are more likely to remain in the informal sector or outside the labour market. Therefore, education in BRICS+ countries must be seen as a key precondition for women’s economic inclusion and deeper social transformation.

Table 1 summarizes the key trends observed in female educational attainment across BRICS+ countries. The results indicate strong stratification between states with near-universal coverage of secondary and tertiary education (Russia, UAE, partly China and Brazil) and those where access to education for women remains structurally limited (Ethiopia, India, Indonesia).

Table 1. Comparative overview of women’s educational attainment trends in BRICS+ countries (1991-2022)

Country	Primary education-completion trend	Secondary education-completion trend	Tertiary education-completion trend
Russia	Near-universal coverage, stable	Very high, stable	Strong and continuous growth
China	High and improving	High, broad coverage	Moderate but visible growth
Brazil	Strong progress, major improvement	Moderate but increasing	Consistent growth
India	Significant progress but still low	Low completion, major regional gaps	Low inclusion
S. Africa	Stable but unequal	Solid growth but socio-economic disparities	Moderate increase
Egypt	Moderate and improving	Gradual expansion	Moderate growth
Iran	Good improvement in access	Steady expansion	Slow to moderate growth
S. Arabia	High improvement due to reforms	Strong increase	Rapid growth, especially last decade
UAE	High and stable	Very high	High & accelerating (women > men)
Ethiopia	Very low, slow improvement	Very low	Minimal inclusion
Indonesia	Moderate progress	Low-moderate	Low

Source: Author’s calculation based on World Bank - World Development Indicators (2024)

Women's Labour Force Participation and Employment

World Bank data (World Development Indicators, 2024) on women's labour force participation, employment and unemployment in BRICS+ countries over the period 1991-2022 (World Bank, 2024) indicate deep structural differences in the degree of women's economic integration.

To assess the extent to which educational progress has translated into economic inclusion, Figures 2-4 present key labour market indicators for women in BRICS+ countries, including labour force participation, employment and unemployment, comparing the initial year (1991) and the most recent available year (2022).

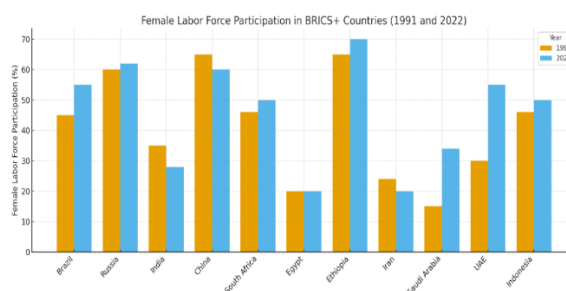


Figure 2. Female labour force participation in BRICS+ countries, 1991 and 2022.
Source: World Bank, World Development Indicators (2024)

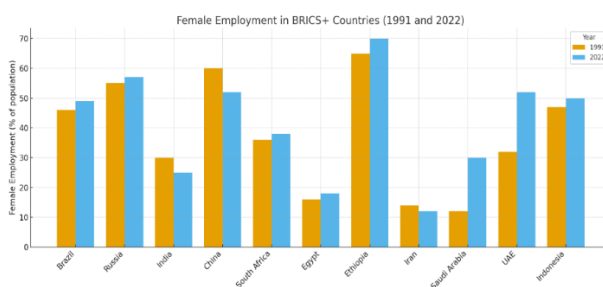


Figure 3. Female employment in BRICS+ countries, 1991 and 2022.
Source: World Bank, World Development Indicators (2024)

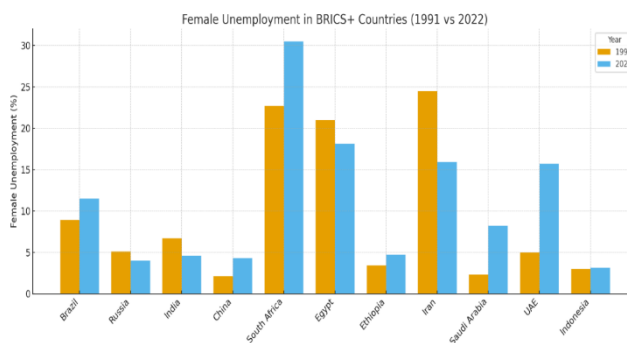


Figure 4. Female unemployment in BRICS+ countries, 1991 and 2022.
Source: World Bank, World Development Indicators (2024)

While significant progress has been made in some countries, persistent barriers still exist in others that limit women's full participation in the formal economy.

With regard to female labour force participation (Figure 2), Russia stands out as the most stable example, with over 60% of women in the labour force throughout the observed period, a legacy of Soviet policies of high inclusion. Brazil has recorded a gradual increase – from around 44% at the beginning of the period to over 55% in recent years. China shows a slightly declining trend (from around 68% to around 63%), which can be linked to demographic changes and economic restructuring. India remains at the lowest level, with a decline from around 34% to below 30%, which points to strong cultural and socio-economic barriers despite rising educational attainment (Kabeer, 2012). South Africa fluctuates around 50% with pronounced oscillations, while Egypt and Iran record persistently low rates (15-23%). Saudi Arabia and the UAE are examples of reform policies: Saudi Arabia has raised women's participation from around 15% to more than 30%, and the UAE from around 30% to significantly higher levels, in line with modernisation agendas.

Employment-to-population ratios further highlight these differences (Figure 3). Russia continues to record high levels of female employment (above 55%), reflecting a more stable institutional framework and a long tradition of women's participation in the economy. Brazil maintains relatively stable values of around 45-50%, while China reached one of the highest rates (around 65%) in the early 2000s, followed by a subsequent decline. India remains at a very low level (20-30%), reflecting a combination of traditional gender roles and the under-integration of women into the formal sector. South Africa fluctuates between 30-38%, while Egypt and Iran maintain persistently low rates (10-18%). Saudi Arabia has increased female employment from around 13% to almost 30%, and the UAE from around 30% to over 50%. Ethiopia, with rates above 70% in some years, is a specific case in which high employment levels reflect the dominance of agricultural and informal sectors rather than high-quality economic inclusion.

Data on female unemployment rates (Figure 4) confirm the existence of structural weaknesses in labour markets across several BRICS+ countries. South Africa has consistently recorded one of the highest female unemployment rates in the world (often over 25%), indicating chronic labour market dysfunction. Egypt and Iran also have high levels (18-20%), while Brazil has seen fluctuations - from around 8% in the 1990s to over 12% in the last decade. In contrast, Russia has maintained moderate levels (5-10%), with a decline after 2010, indicating relatively more effective institutional mechanisms. India and Indonesia have formally low unemployment rates (4-6%), but these indicators mask the fact that a large number of women work in the informal sector without adequate social protection. Saudi Arabia has reduced female unemployment from over 20% to around 11% in the last decade, while the UAE records the lowest levels in the group (2-3%).

Overall, these indicators point to a deep gap between educational achievements and the actual economic integration of women in many BRICS+ countries. While some countries (Russia, Brazil, UAE) are showing progress in transferring educational gains to the labour market, in others (India, Egypt, Iran, Ethiopia) women remain structurally marginalised at the fringes of economic activity. This confirms that improving education, although necessary, is not sufficient without simultaneously building institutional mechanisms for

equal access to employment, combating discrimination and recognising unpaid work as part of economic contribution. These findings are consistent with the conclusions of the BRICS Report on Gender Equality and Women's Empowerment (BRICS, 2021), which highlights the gap between educational progress and actual labour market integration of women across member countries.

CONCLUSION

The analysis of education, female labour force participation and employment in BRICS+ countries has shown that significant progress has been made in recent decades, but that deep-rooted differences between countries and regions persist. The data clearly confirm that education is a prerequisite for greater participation of women in economic and social activity (Barro and Sala-i-Martin, 2004): countries with higher levels of completed primary, secondary and tertiary education also have higher female labour force participation rates. However, education alone is not sufficient to ensure full economic integration of women.

Despite rising educational achievements, many BRICS+ countries still experience low levels of women's economic inclusion, high unemployment rates and limited access to the formal labour market. This points to structural and institutional barriers that education alone cannot overcome. Cultural norms, gender stereotypes, unpaid domestic work and insufficient institutional support (family policies, access to finance, anti-discrimination mechanisms) are obstacles that limit the full realisation of the potential of the female workforce.

The data show that countries which have achieved universal literacy and high secondary education coverage (Russia, China, the UAE) have also created more stable conditions for women's economic inclusion. In contrast, countries such as India, Egypt and Ethiopia, where a significant share of the female population still does not complete primary or secondary education, have extremely low rates of female labour force participation. This confirms the key assumption of this paper - that education is a necessary but not sufficient condition for women's economic emancipation.

The gap between educational attainment and real employment opportunities remains deep, indicating the existence of multiple and long-standing cultural, institutional and economic barriers. Women continue to be over-represented in informal sectors, bear the burden of unpaid domestic and care work, and have limited access to leadership positions and entrepreneurial resources.

Based on the analysis conducted, it can be concluded that reducing the gender gap in the labour market requires stronger institutional support for women, the development of childcare infrastructure and greater access to financial instruments. Incentives for formal employment, equal-pay-for-equal-work campaigns and measures that stimulate female entrepreneurship, especially in rural areas, are needed. Raising awareness about the value of unpaid work is also of utmost importance - by including domestic and care work in economic statistics and designing policies that distribute care more evenly between men and women. Linking education to employment, improving the quality of education and

greater integration of women into sectors with high added value (digital economy, science, technological innovation) can significantly improve their economic position.

In conclusion, the paper shows that the economic development of BRICS+ countries can only be sustainable and inclusive if macroeconomic growth is coupled with systemic gender equality policies. The integration of women into the formal economy is not only a matter of social justice, but also a factor of competitiveness, innovation and long-term growth. As a grouping that is increasingly shaping the global economic order, BRICS+ has the potential to become an example of a new development model - one in which economic dynamism goes hand in hand with social inclusion and equality. Recent BRICS+ policy documents also emphasise the importance of integrating gender equality objectives into broader economic development strategies (BRICS+, 2024).

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IDENTIFICATION OF OPTIMAL WASTEWATER SYSTEM PARAMETERS AIMED AT MAXIMIZING ECONOMIC PERFORMANCE

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Abstract: In this article, a selection procedure for identifying the most influential parameters of a wastewater treatment system with respect to maximizing economic profit is presented. Optimal wastewater treatment configurations require the adjustment of numerous system parameters to obtain economically efficient solutions. Such optimal solutions are commonly defined in terms of maximizing economic performance, typically expressed through minimizing the total cost of the wastewater treatment system. However, applying classical analytical optimization methods to this problem is time-consuming and computationally demanding due to the system's high degree of nonlinearity. Accordingly, the primary objective of this study was to determine which parameters of the wastewater treatment system exert the greatest influence on overall economic profit. To support this selection process, an Adaptive Neuro-Fuzzy Inference System (ANFIS) was employed, as this method is well-suited for handling nonlinear relationships and redundant datasets. The results indicate that system size is the dominant factor affecting economic outcomes. The obtained findings have practical significance, as they provide guidance for selecting the most economically favorable configuration for a given wastewater treatment system.

Keywords: Wastewater, Economic profit, Optimal solution, ANFIS.

INTRODUCTION

Wastewater treatment systems are inherently complex, comprising numerous interdependent parameters that influence overall process performance. To achieve substantial economic benefits in rural wastewater treatment applications, it is essential to identify those parameters that exert the greatest impact on economic profit. These key parameters simultaneously represent the primary contributors to the total costs of the wastewater treatment system. Consequently, economic profit is typically evaluated through the minimization of total system costs.

The selection of an optimal solution is of critical importance when applying economic criteria to wastewater treatment system design and operation (Abdelf-Fatah, 2018). Research on the sustainable development of wastewater systems consistently highlights the necessity of integrating environmental, social, and economic dimensions within the decision-making process (Ansari et al., 2019). Various technological configurations have been investigated to enhance wastewater treatment performance. For example, two

technological setups were analyzed in (Jokanović et al., 2017), forming the basis for four alternative wastewater reclamation scenarios. In another study, a sequential approach to hydrogen and methane production from dairy industry wastewater was explored using *Enterobacter aerogens* and methanogenic bacteria derived from cow dung, demonstrating simultaneous pollutant reduction and biofuel generation (Novković-Cvetković et al., 2019). A thermo-economic analysis of hybrid solar conventional energy supply in a zero-liquid-discharge plant was presented in (Elreedy et al., 2019), while biogas production through anaerobic digestion of organic waste and manure has shown potential to reduce greenhouse gas emissions across multiple sectors, including waste management, transportation, energy, and agriculture (Deneva et al., 2017).

Further investigations include the development of a wastewater metabolism input–output model aimed at providing a novel framework for sustainable industrial wastewater flow assessment among economic sectors (Kothari et al., 2017). Advances in nanofiltration membrane (NF) technologies continue to represent a crucial component within modern wastewater treatment processes (Lyng et al., 2018). Additionally, independent hydrogen production from petrochemical wastewater containing mono-ethylene glycol (MEG) has been comprehensively evaluated under psychrophilic conditions using an anaerobic sequencing batch reactor (ASBR) (Mladenovic et al., 2016). Domestic wastewater, owing to its high nutrient content, also offers substantial potential for nutrient recovery through dedicated wastewater treatment technologies (Nikolić et al., 2018).

Classical analytical optimization approaches applied to wastewater treatment systems require considerable time and computational effort due to the pronounced nonlinearity of the governing equations. Therefore, the principal objective of this study is to identify the parameters of a wastewater treatment system that have the most significant influence on its economic profitability. To facilitate this selection process, an Adaptive Neuro-Fuzzy Inference System (ANFIS) was employed (Murashko et al., 2018; Najafi et al., 2019; Padilla-Rivera and Güereca, 2019; Nikolić et al., 2018; Zheng et al., 2019), as this method is particularly suitable for handling nonlinear, redundant, and complex datasets.

MATERIAL AND METHODS

Database of Wastewater System

To implement the ANFIS model, it was necessary to prepare a comprehensive database consisting of input-output data samples. Table 1 presents all variables used in the study. The input parameters include: system size; elongation factor (i.e., the length-to-width ratio of the settlement); dispersion factor (defined as the ratio between the number of households and the sewer network length); vertical terrain uniformity; proximity to the urban centre (distance between the settlement and the nearest urban node); degree of settlement clustering (distance between neighboring settlements); and distance between the wastewater treatment plant and the settlement. The total construction cost of the wastewater treatment system was used as the output variable.

Table 1. Input and output parameters of the wastewater system

Input 1 Size	Input 2 Elongation	Input 3 Dispersion	Input 4 Uniformity	Input 5 Vicinity	Input 6 Grouping	Input 7 Distance	Output Total costs
284.9	3	0.02	4.96	6.01	1.17	0.96	1039705.4

ANFIS Methodology

ANFIS network has five layers as it shown in Figure 1. The main core of the ANFIS network is fuzzy inference system. Layer 1 receives the inputs and convert them in the fuzzy value by membership functions. In this study bell shaped membership function is used since the function has the highest capability for the regression of the nonlinear data.



Figure 1. ANFIS layers

Bell-shaped membership functions is defined as follows:

$$\mu(x) = bell(x; a_i, b_i, c_i) = \frac{1}{1 + \left[\frac{(x - c_i)^2}{a_i^2} \right]^{b_i}} \quad (1)$$

where $\{a_i, b_i, c_i\}$ is the parameters set and x is input.

Second layer multiplies the fuzzy signals from the first layer and provides the firing strength of as rule. The third layer is the rule layers where all signals from the second layer are normalized. The fourth layer provides the inference of rules, and all signals are converted in crisp values. The final layers summarized all signals and provided the output crisp value.

RESULTS AND DISCUSSION

Accuracy Indices

Performances of the proposed models are presented as root means square error (RMSE), Coefficient of determination (R^2) and Pearson coefficient (r) as follows:

1) RMSE

$$RMSE = \sqrt{\frac{\sum_{i=1}^n (P_i - O_i)^2}{n}}, \quad (2)$$

2) Pearson correlation coefficient (r)

$$r = \frac{n \left(\sum_{i=1}^n O_i \cdot P_i \right) - \left(\sum_{i=1}^n O_i \right) \cdot \left(\sum_{i=1}^n P_i \right)}{\sqrt{\left(n \sum_{i=1}^n O_i^2 - \left(\sum_{i=1}^n O_i \right)^2 \right) \cdot \left(n \sum_{i=1}^n P_i^2 - \left(\sum_{i=1}^n P_i \right)^2 \right)}} \quad (3)$$

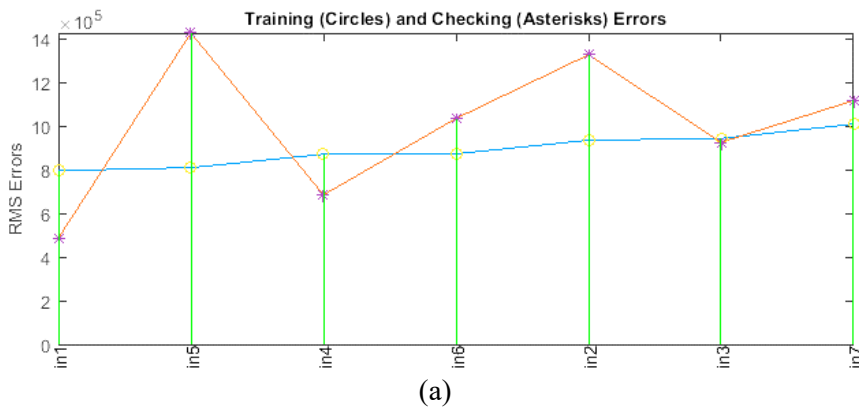
3) Coefficient of determination (R^2)

$$R^2 = \frac{\left[\sum_{i=1}^n (O_i - \bar{O}_i) \cdot (P_i - \bar{P}_i) \right]^2}{\sum_{i=1}^n (O_i - \bar{O}_i)^2 \cdot \sum_{i=1}^n (P_i - \bar{P}_i)^2} \quad (4)$$

where P_i and O_i are known as the experimental and forecast values, respectively, and n is the total number of datasets.

ANFIS Results

Table 3 shows the prediction errors for the total costs or economic profit of the wastewater system for single, two and three input parameters. Training RMSE shows influence of the inputs for the wastewater total costs. Smaller training errors have more influence on the wastewater total costs. Checking RMSE is used for overfitting tracking between training and checking data. Here one can see there is small overfitting for two and three input combinations since checking errors do not track training errors very well. As can be seen for single input parameters influence in Figure 2a the input parameters system size has the smallest training error therefore largest influence on the total costs of the wastewater system. Figure 2b shows two parameters' combinations and their corresponding training and checking errors for the total costs prediction of the wastewater system where combination of vicinity and distance has the smallest training error, hence the largest impact on the economic profit of the wastewater system. Finally Figure 2c shows three input combinations where one can see that the parameter system size, dispersion and vicinity form the optimal combination of three parameters for the total costs prediction of the wastewater system. Tables 2-4 show the numerical training and checking errors for all inputs combinations of the total costs prediction of the wastewater system where bolded values represent the optimal combinations.



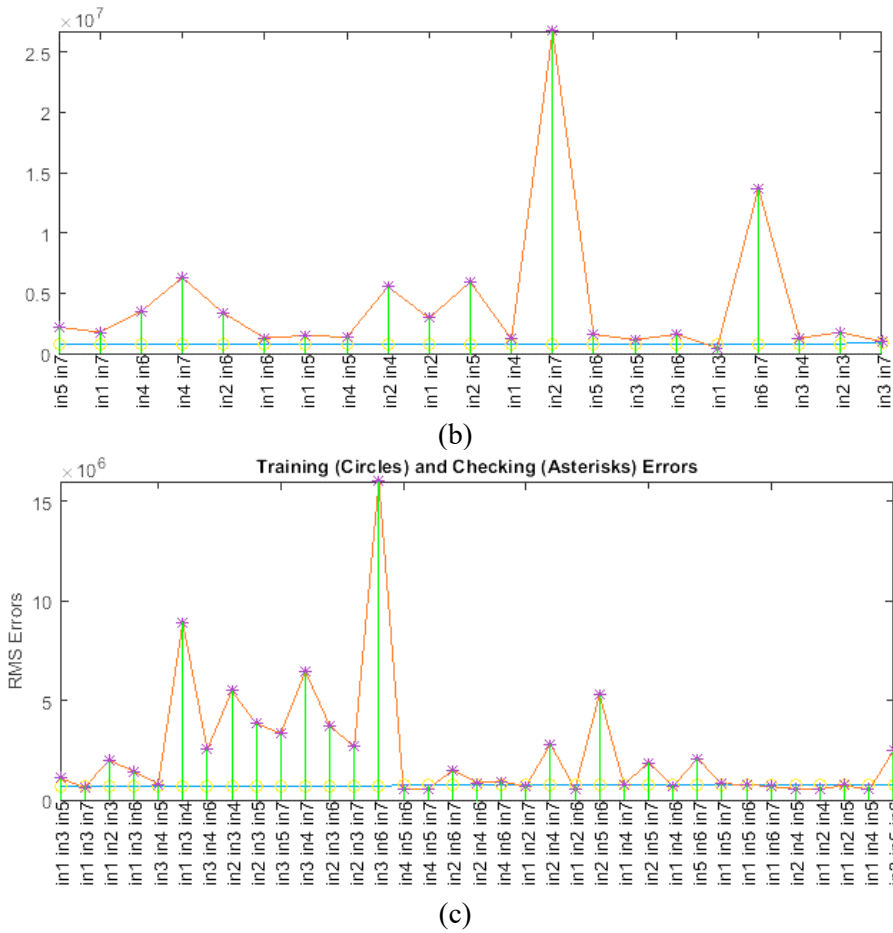


Figure 2. Inputs' influence on the output: (a) single inputs, (b) two inputs, (c) three inputs

Table 2. Single inputs' influence on the output

ANFIS model 1: in1 --> trn=795052.3800	chk=486121.6677
ANFIS model 2: in2 --> trn=934493.0105	chk=1325577.0070
ANFIS model 3: in3 --> trn=942358.2941	chk=924852.5804
ANFIS model 4: in4 --> trn=870057.7917	chk=684031.8942
ANFIS model 5: in5 --> trn=809001.7197	chk=1425160.2330
ANFIS model 6: in6 --> trn=872226.5836	chk=1033930.6644
ANFIS model 7: in7 --> trn=1008353.1837	chk=1116116.8827

Table 3. Two inputs' influence on the output

ANFIS model 1: in1 in2 --> trn=724825.7907	chk=2931102.1642
ANFIS model 2: in1 in3 --> trn=774927.9722	chk=462781.9739
ANFIS model 3: in1 in4 --> trn=724825.9920	chk=1199555.0113
ANFIS model 4: in1 in5 --> trn=724825.7715	chk=1471737.5135
ANFIS model 5: in1 in6 --> trn=721190.5829	chk=1284921.6765
ANFIS model 6: in1 in7 --> trn=721190.0175	chk=1756868.7562
ANFIS model 7: in2 in3 --> trn=813386.0264	chk=1746867.8528
ANFIS model 8: in2 in4 --> trn=724825.7716	chk=5531286.3668
ANFIS model 9: in2 in5 --> trn=724825.8296	chk=5920287.0186
ANFIS model 10: in2 in6 --> trn=721190.1054	chk=3351655.9556

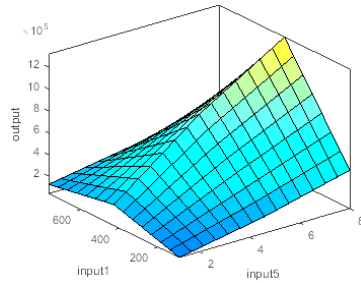
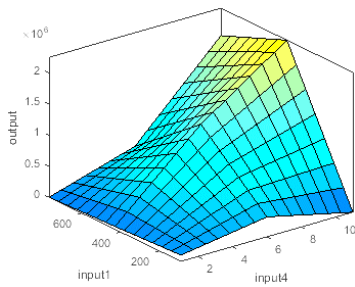
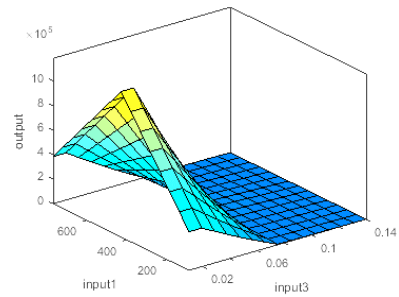
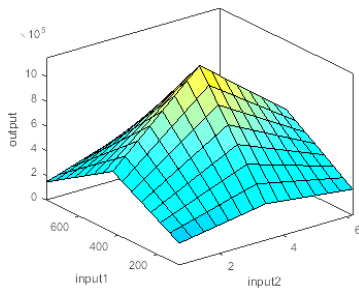
ANFIS model 11: in2 in7 -->	trn=732752.1817	chk=26719811.3762
ANFIS model 12: in3 in4 -->	trn=791683.6982	chk=1265159.0159
ANFIS model 13: in3 in5 -->	trn=762214.7836	chk=1137596.5035
ANFIS model 14: in3 in6 -->	trn=772622.1657	chk=1570964.2008
ANFIS model 15: in3 in7 -->	trn=873703.5481	chk=975834.5975
ANFIS model 16: in4 in5 -->	trn=724825.7715	chk=1362411.5779
ANFIS model 17: in4 in6 -->	trn=721190.0175	chk=3462676.9435
ANFIS model 18: in4 in7 -->	trn=721190.1050	chk=6293597.5250
ANFIS model 19: in5 in6 -->	trn=756651.3649	chk=1562383.1620
ANFIS model 20: in5 in7 -->	trn=721190.0066	chk=2184588.3894
ANFIS model 21: in6 in7 -->	trn=788304.2828	chk=13688525.4462

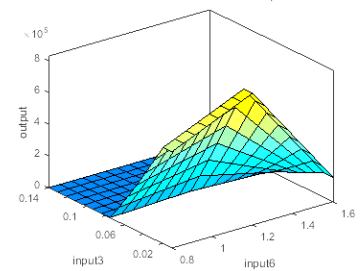
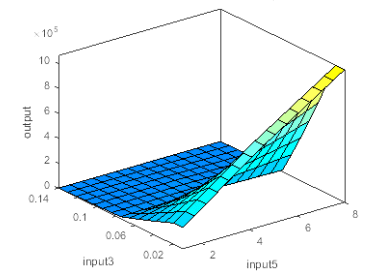
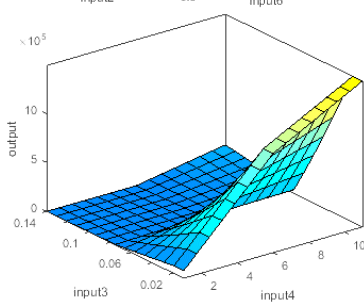
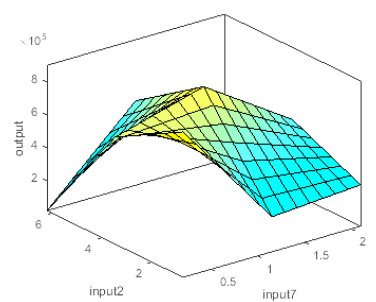
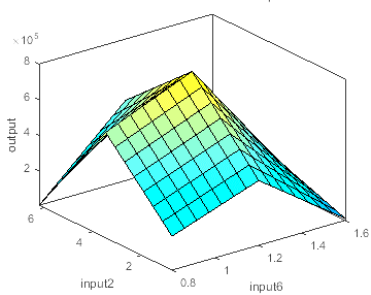
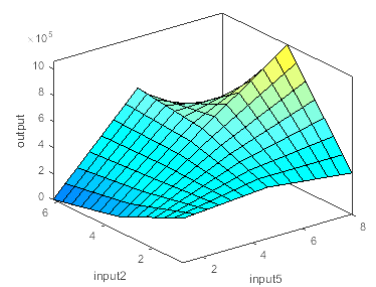
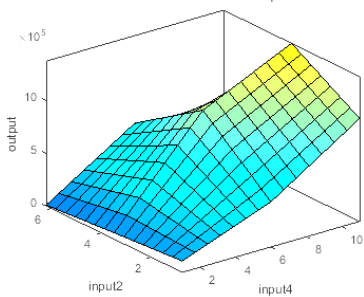
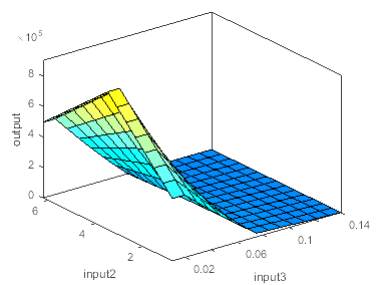
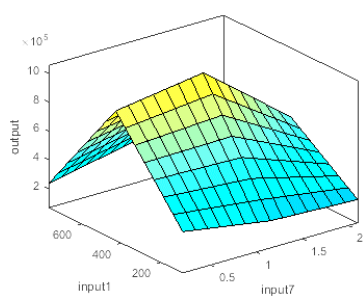
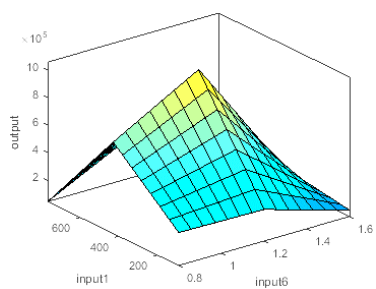
Table 4. Three inputs' influence on the output

ANFIS model 1: in1 in2 in3 -->	trn=717062.3526,	chk=1991830.1402
ANFIS model 2: in1 in2 in4 -->	trn=724825.7715	chk=541577.8279
ANFIS model 3: in1 in2 in5 -->	trn=724825.7719	chk=727232.1725
ANFIS model 4: in1 in2 in6 -->	trn=721190.0012	chk=550695.9397
ANFIS model 5: in1 in2 in7 -->	trn=721190.0012	chk=676052.4503
ANFIS model 6: in1 in3 in4 -->	trn=717062.3621	chk=8919082.8974
ANFIS model 7: in1 in3 in5 -->	trn=717062.3524	chk=1080947.4127
ANFIS model 8: in1 in3 in6 -->	trn=717062.3528	chk=1437260.3746
ANFIS model 9: in1 in3 in7 -->	trn=717062.3526	chk=642086.9245
ANFIS model 10: in1 in4 in5 -->	trn=724825.7729	chk=515033.0225
ANFIS model 11: in1 in4 in6 -->	trn=721190.0012	chk=673446.7701
ANFIS model 12: in1 in4 in7 -->	trn=721190.0012	chk=774892.2500
ANFIS model 13: in1 in5 in6 -->	trn=721190.0068	chk=780201.7730
ANFIS model 14: in1 in5 in7 -->	trn=721190.0028	chk=799408.8123
ANFIS model 15: in1 in6 in7 -->	trn=721190.0161	chk=667044.1730
ANFIS model 16: in2 in3 in4 -->	trn=717062.3679	chk=5470009.1720
ANFIS model 17: in2 in3 in5 -->	trn=717062.3735	chk=3823271.6177
ANFIS model 18: in2 in3 in6 -->	trn=717062.5549	chk=3718324.6971
ANFIS model 19: in2 in3 in7 -->	trn=717063.6139	chk=2667008.2019
ANFIS model 20: in2 in4 in5 -->	trn=724825.7714	chk=563687.6772
ANFIS model 21: in2 in4 in6 -->	trn=721190.0012	chk=861955.0153
ANFIS model 22: in2 in4 in7 -->	trn=721190.0012	chk=2797595.2049
ANFIS model 23: in2 in5 in6 -->	trn=721190.0012	chk=5292965.2192
ANFIS model 24: in2 in5 in7 -->	trn=721190.0012	chk=1869850.4545
ANFIS model 25: in2 in6 in7 -->	trn=721190.0012	chk=1486697.1116
ANFIS model 26: in3 in4 in5 -->	trn=717062.3536	chk=779282.7756
ANFIS model 27: in3 in4 in6 -->	trn=717062.3626	chk=2528292.0317
ANFIS model 28: in3 in4 in7 -->	trn=717062.4691	chk=6453906.4347
ANFIS model 29: in3 in5 in6 -->	trn=730327.4828	chk=2471711.0046
ANFIS model 30: in3 in5 in7 -->	trn=717062.3805	chk=3332526.6893
ANFIS model 31: in3 in6 in7 -->	trn=717679.4983	chk=15975926.5099
ANFIS model 32: in4 in5 in6 -->	trn=721190.0012	chk=539168.0373
ANFIS model 33: in4 in5 in7 -->	trn=721190.0012	chk=548010.1157
ANFIS model 34: in4 in6 in7 -->	trn=721190.0012	chk=925331.3952
ANFIS model 35: in5 in6 in7 -->	trn=721190.0023	chk=2079240.9627

Figure 3 shows the ANFIS decision surfaces for the economic profit of wastewater treatment system based on different combinations of inputs. The combinations created based on mean values of the inputs and can be listed as follows:

-
1. *Input 1* *Input 2* 0.02616 4.964 6.015 1.178 0.9673
 2. *Input 1* 3.008 *Input 3* 4.964 6.015 1.178 0.9673
 3. *Input 1* 3.008 0.02616 *Input 4* 6.015 1.178 0.9673
 4. *Input 1* 3.008 0.02616 4.964 *Input 5* 1.178 0.9673
 5. *Input 1* 3.008 0.02616 4.964 6.015 *Input 6* 0.9673
 6. *Input 1* 3.008 0.02616 4.964 6.015 1.178 *Input 7*
 7. 284.9 *Input 2* *Input 3* 4.964 6.015 1.178 0.9673
 8. 284.9 *Input 2* 0.02616 *Input 4* 6.015 1.178 0.9673
 9. 284.9 *Input 2* 0.02616 4.964 *Input 5* 1.178 0.9673
 10. 284.9 *Input 2* 0.02616 4.964 6.015 *Input 6* 0.9673
 11. 284.9 *Input 2* 0.02616 4.964 6.015 1.178 *Input 7*
 12. 284.9 3.008 *Input 3* *Input 4* 6.015 1.178 0.9673
 13. 284.9 3.008 *Input 3* 4.964 *Input 5* 1.178 0.9673
 14. 284.9 3.008 *Input 3* 4.964 6.015 *Input 6* 0.9673
 15. 284.9 3.008 *Input 3* 4.964 6.015 1.178 *Input 7*
 16. 284.9 3.008 0.02616 *Input 4* *Input 5* 1.178 0.9673
 17. 284.9 3.008 0.02616 *Input 4* 6.015 *Input 6* 0.9673
 18. 284.9 3.008 0.02616 *Input 4* 6.015 1.178 *Input 7*
 19. 284.9 3.008 0.02616 4.964 *Input 5* *Input 6* 0.9673
 20. 284.9 3.008 0.02616 4.964 *Input 5* 1.178 *Input 7*
 21. 284.9 3.008 0.02616 4.964 6.015 *Input 6* *Input 7*
-





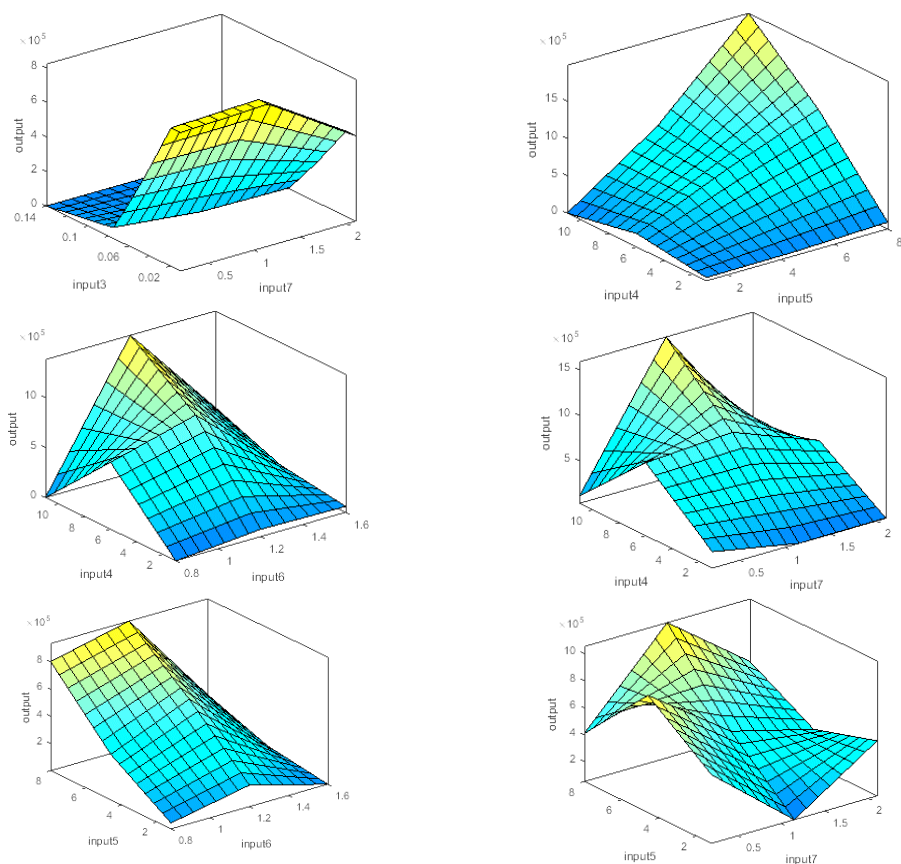


Figure 3. ANFIS decision surfaces for the economic profit of wastewater treatment system based on different combinations of inputs

CONCLUSION

In this article, adaptive neuro fuzzy inference system (ANFIS) is used for selection procedures in order to identify the most influential parameters of wastewater treatment system based on economic profit. Results revealed that the size of the system has the most influence on economic profit. Furthermore, obtained solutions could be of practical importance since one could select which solutions are the most suitable for particular wastewater treatment system.

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EMOTIONAL INTELLIGENCE AND PSYCHOLOGICAL FLEXIBILITY AS FACTORS OF SUSTAINABLE DEVELOPMENT

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Abstract: This paper explores the role of emotional intelligence and psychological flexibility as key psychological factors of sustainable development. Emotional intelligence contributes to more effective decision-making, stress regulation, and the development of constructive interpersonal relationships, while psychological flexibility enables efficient adaptation to change and the maintenance of well-being under conditions of uncertainty. Through the analysis of contemporary theoretical models and relevant research, the paper highlights that these two competencies strengthen resilience, innovation, and long-term stability within organizations and communities. It concludes that the development of internal human capacities is a fundamental component of sustainable strategies and that emotional intelligence and psychological flexibility play an increasingly important role in shaping sustainable systems.

Keywords: Emotional intelligence, Psychological flexibility, Sustainable development, Resilience, Human factors

INTRODUCTION

The contemporary concept of sustainable development requires an integrated understanding of economic, social, and psychological factors that shape long-term behavioural patterns of individuals, organizations, and communities. Although sustainability has traditionally been viewed through ecological and economic dimensions, recent research highlights the crucial role of human capacities in adapting to global challenges. In this context, emotional intelligence and psychological flexibility emerge as two important factors that contribute to resilience, high-quality decision-making, and effective change management.

Emotional intelligence enables individuals to recognize, understand, and regulate their own emotions as well as the emotions of others, which facilitates dealing with complex situations and uncertainty. Psychological flexibility, understood as the ability to behave adaptively in accordance with one's values and environmental demands, supports stability and resilience under conditions of change. Together, these abilities enhance the capacity of individuals and systems to respond to sustainability challenges in a constructive and long-term manner.

The aim of this paper is to examine how emotional intelligence and psychological flexibility support sustainable development, and how these psychological dimensions contribute to building more resilient, innovative, and stable organizations and communities. The focus is on the connection between human factors and the principles of sustainability, as well as the analysis of their potential to improve decision-making, adaptation processes, and stress management within modern social and organizational contexts.

THEORETICAL FRAMEWORK

Emotional Intelligence

Emotional intelligence represents a set of abilities that enables an individual to recognize, understand, and effectively manage their own emotions, as well as the emotions of other people. According to the most established models, emotional intelligence includes four core dimensions: emotion perception, understanding emotional signals, emotion regulation, and the functional application of emotions in decision-making processes. These abilities have a direct impact on interpersonal relationships, communication quality, and the capacity to cope with challenges in dynamic environments.

In the context of sustainable development, emotional intelligence contributes to the development of both collective and individual responsibility, ethical behavior, and a long-term perspective in decision-making. Individuals with higher emotional intelligence demonstrate greater stress-management capacity, adapt more efficiently to change, and help create stable and cohesive organizational cultures, all of which are essential components of sustainable systems.

Psychological Flexibility

Psychological flexibility refers to an individual's ability to adapt to environmental demands, remains connected to personal values, and chooses behavior that is most useful in a given moment even when facing discomfort, stress, or uncertainty. This concept is grounded in contemporary psychological principles, especially models that emphasize acceptance of internal experiences, cognitive flexibility, and value-driven action.

Developed psychological flexibility is associated with higher resilience, easier decision-making in changing circumstances, and a stronger capacity for long-term planning. In the context of sustainable development, psychological flexibility enables individuals and organizations to better respond to complex challenges such as uncertainty, innovation demands, and the need to transform established behavioral patterns.

Human Factors in Sustainable Development

Sustainable development has traditionally been viewed through three dimensions: environmental, economic, and social. However, contemporary approaches emphasize that the success of sustainable strategies greatly depends on the psychological and emotional capacities of individuals and communities. Factors such as emotional self-regulation, cognitive flexibility, and the ability to make informed decisions contribute to long-term stability, innovation, and responsible resource use. In this sense, emotional intelligence and

psychological flexibility become key elements of the “human infrastructure” of sustainable development. They influence motivation, behavior, relationships within organizations, and the capacity of communities to cope with change and crises. Thus, human factors are positioned as an indispensable component of strategies aimed at building a sustainable and stable future.

THE RELATIONSHIP BETWEEN EMOTIONAL INTELLIGENCE, PSYCHOLOGICAL FLEXIBILITY AND SUSTAINABLE DEVELOPMENT

Interdisciplinary literature increasingly confirms that sustainable development depends not only on economic and environmental strategies, but also on the psychological capacities of individuals and communities (Senge, 2006). Emotional intelligence and psychological flexibility represent key human resources that shape how organizations and societies respond to complexity, uncertainty, and long-term challenges. Within this framework, these two competencies contribute directly to resilience, ethical decision-making, and adaptive capacity, which are central to sustainable development.

The Contribution of Emotional Intelligence to Sustainable Development

Emotional intelligence plays a crucial role in sustainable development through its impact on decision-making, emotional regulation, and ethical behavior. According to Mayer et al. (2004), emotionally intelligent individuals are better able to interpret emotional information and respond adaptively in complex and uncertain situations.

In organizational and societal contexts, emotional intelligence supports sustainable development by enhancing interpersonal cooperation, facilitating constructive conflict management, and promoting long-term, responsible decision-making. Individuals with higher levels of emotional intelligence demonstrate greater stress, tolerance and emotional stability, which reduces impulsive behavior and strengthens resilience in periods of change.

As emphasized by Goleman (1998), emotionally intelligent organizations are more likely to develop cultures of responsibility, trust, and ethical conduct. Key preconditions for sustainable practices.

Psychological Flexibility and Sustainable Development

Psychological flexibility refers to the ability to remain open to internal experiences, adapt to changing circumstances, and act in accordance with personal values despite discomfort or uncertainty (Hayes, 2016). This capacity is particularly relevant in the context of sustainable development, where constant adaptation and transformation are unavoidable.

Individuals with higher psychological flexibility demonstrate greater tolerance of uncertainty, reduced emotional reactivity, and a stronger orientation toward long-term goals. These qualities support sustainable development by enabling rational planning, openness to innovation, and resilience in dynamic environments (Seligman and Csikszentmihalyi, 2000).

At the organizational level, psychological flexibility facilitates learning from change, faster adaptation to new conditions, and the integration of innovative solutions, all of which are essential for sustainable systems.

The Synergy of Emotional Intelligence and Psychological Flexibility in Sustainability

Although emotional intelligence and psychological flexibility are distinct constructs, their combined effect creates a strong psychological foundation for sustainable development. Emotional intelligence enables emotional awareness, regulation, and high-quality social interaction, while psychological flexibility allows adaptive, value-driven action under conditions of uncertainty.

Together, these capacities support resilience, reduce maladaptive stress responses, and promote long-term, values-based decision-making. Contemporary sustainability frameworks increasingly recognize that such human factors represent the psychological infrastructure upon which sustainable organizations and communities are built (OECD, 2021; UNDP).

THE MODEL OF THE INFLUENCE OF EMOTIONAL INTELLIGENCE AND PSYCHOLOGICAL FLEXIBILITY ON SUSTAINABLE DEVELOPMENT

Understanding sustainable development requires an integrative approach that includes not only economic, environmental, and social dimensions, but also the psychological mechanisms that shape human behavior within organizations and communities. Emotional intelligence and psychological flexibility represent two complementary human capacities that significantly influence decision-making quality, stress regulation, resilience, and adaptive behavior core elements of sustainable systems (Senge, 2006; UNDP, 2021).

Emotional intelligence contributes to sustainability by enabling individuals to recognize and regulate emotional responses, maintain constructive interpersonal relationships, and consider the long-term consequences of their actions. These capacities support ethical behavior, responsible leadership, and socially aware decision-making, which are essential for sustainable organizational cultures (Mayer et al., 2004; Goleman, 1998).

Psychological flexibility complements emotional intelligence by enabling individuals and organizations to remain open to change, tolerate uncertainty, and act in accordance with values despite stress or discomfort (Hayes, 2016). This capacity reduces emotional reactivity, enhances learning from experience, and supports innovation in complex and rapidly changing environments.

The interaction between emotional intelligence and psychological flexibility creates a psychological foundation for resilience and long-term stability. Emotionally intelligent individuals are better able to understand emotional dynamics within systems, while psychological flexibility enables adaptive and value-driven responses to these dynamics. Together, these competencies promote sustainable decision-making, effective stress management, and the capacity for continuous adaptation.

Based on this integrative perspective, sustainable development can be understood as an outcome of emotionally aware, psychologically flexible individuals and systems. Such systems are better equipped to balance short-term demands with long-term goals, respond constructively to uncertainty, and maintain social responsibility over time. This model positions emotional intelligence and psychological flexibility as core components of the human infrastructure of sustainable development.

DISCUSSION

The theoretical analysis presented in this paper indicates that emotional intelligence and psychological flexibility represent essential psychological resources for sustainable development. Rather than functioning as isolated competencies, these capacities jointly shape how individuals and organizations perceive challenges, regulate stress, and make long-term decisions in complex and uncertain environments.

Emotional intelligence supports sustainable behavior by enabling individuals to recognize emotional dynamics within themselves and others, maintain constructive relationships, and integrate ethical and social considerations into decision-making processes. In the context of sustainability, this emotional awareness reduces impulsive reactions and promotes responsibility, cooperation, and long-term orientation qualities that are indispensable for sustainable organizational cultures.

Psychological flexibility, on the other hand, plays a critical role in enabling adaptive functioning under conditions of uncertainty and change. Sustainable development inherently involves transformation, requiring individuals and systems to tolerate ambiguity, adjust established patterns, and remain aligned with core values despite pressure. Psychological flexibility enhances this capacity by reducing emotional reactivity, supporting learning from experience, and fostering openness to innovation.

The integration of emotional intelligence and psychological flexibility creates a synergistic psychological foundation for sustainability. While emotional intelligence enables awareness and regulation of emotional processes, psychological flexibility enables action despite emotional discomfort. Together, these competencies support resilience, values-based decision-making, and adaptive capacity, allowing organizations and communities to respond constructively to long-term sustainability challenges.

From a practical perspective, these findings highlight the importance of investing in the development of internal human capacities as part of sustainable strategies. Training programs, leadership development initiatives, and organizational policies that strengthen emotional intelligence and psychological flexibility can enhance resilience, promote psychological safety, and support innovation. For policymakers and organizational leaders, this implies that sustainable development should be approached not only through technical solutions and regulatory frameworks, but also through systematic support for psychological competencies that enable responsible and adaptive behavior.

The contribution of this paper lies in its integrative perspective. While existing literature increasingly acknowledges the role of soft skills in sustainability, this paper conceptually links emotional intelligence and psychological flexibility within a unified framework of

sustainable development. By positioning these competencies as core elements of the human infrastructure of sustainability, the paper provides a clearer understanding of how internal psychological resources support long-term stability, resilience, and social responsibility.

CONCLUSION

This paper examined emotional intelligence and psychological flexibility as key psychological factors supporting sustainable development in organizations and communities. In the context of increasing complexity, uncertainty, and global challenges, the findings suggest that sustainable development cannot be achieved solely through technical, economic, or regulatory solutions. Instead, it requires well-developed internal human capacities that enable responsible decision-making, emotional regulation, adaptability, and long-term orientation.

Emotional intelligence contributes to sustainability by fostering emotional awareness, ethical sensitivity, and constructive interpersonal relationships, while psychological flexibility enables individuals and systems to respond adaptively to change, tolerate uncertainty, and act in accordance with core values. Together, these competencies form a psychological foundation for resilience, innovation, and sustainable action across organizational and societal contexts.

The central message of this paper is that sustainability begins from within. Organizations and communities striving for sustainable development must invest not only in external systems and strategies, but also in the development of emotional and psychological capacities that support stability, responsibility, and adaptability. Emotional intelligence and psychological flexibility should therefore be understood as fundamental resources rather than optional skills within sustainability frameworks.

This paper contributes to the theoretical understanding of sustainable development by integrating emotional intelligence and psychological flexibility into a coherent conceptual model. A key limitation of the study lies in its theoretical nature and the absence of empirical data, which opens opportunities for future research. Further studies could empirically examine the relationships between emotional intelligence, psychological flexibility, and concrete sustainability indicators across different organizational and cultural contexts.

By highlighting the role of internal human capacities, this paper offers a broader perspective on sustainability, one that emphasizes awareness, flexibility, and responsibility as essential conditions for long-term stability and sustainable development.

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KEY ASPECTS OF INSTRUMENTAL COLOUR FOR COMPOSITE BUCKWHEAT EMULSION-TYPE CHICKEN SAUSAGES

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Abstract: Buckwheat is one of the traditionally high-quality crops recognized for its high nutritional and functional value. Emulsion-type chicken sausages modified by adding time-different stored buckwheat flours (FB0, FB3, FB6, and FB9) were analyzed for instrumental colour parameters (L^* , a^* , b^* , C^* , h , S , ΔE). One-way ANOVA test ($p < 0.05$), followed by Tukey's HSD post-hoc test ($p < 0.05$) were used to analyze the data. Added flour slightly affects L^* , and significantly a^* and b^* , where FB0 was lighter, redder and yellower than the other composite products. A significant decrease in C^* and increase in h values caused lower chromatic purity and a more yellow nuance in FB9 (20.65, 45.40). A decrease in S resulted in the greatest attenuation in overall colour perception at FB6, and FB9. An increase trend of ΔE indicating the differentiation of sausages with respect to effect on total colour ($\Delta E \leq 5.10$). The results indicate the potential utilization of long-term stored buckwheat grains (flour) as a functional ingredient and valuable plant-based raw material in the production of composite, technologically justified meat products with sensory acceptable colours for consumers.

Keywords: Emulsion-type sausage, Buckwheat, Composite product, Instrumental colour, Storage

INTRODUCTION

The meat industry is one of the most important branches of the food industry, which requires the continuous introduction of new products, with a special emphasis on modern consumer demands for products enriched with plant ingredients or antioxidants of natural (plant) origin. In the modern meat industry, the addition of plant-based raw materials (cereals, flour, hulls, powder, extracts) to meat product formulations can effectively improve various chemical, nutritional, functional, technological and sensory properties (Yessengaziyeva et al., 2023). For these reasons, formulation development has led to the production of composite products similar to dried fermented or semi-smoked sausages, frankfurter-type sausages, horse meat or chicken patties, pork meatballs (Salejda et al., 2022; Pisinov et al., 2025b).

For human consumption, buckwheat grains are often stored for long periods of time for strategic reasons. Storage conditions determine the preservation of nutritional characteristics for a longer period of time and can affect changes in biological, physical and

chemical properties. There are numerous studies that address this issue (Rakić et al., 2005; Pisinov et al., 2024). These changes negatively affect the quality of flour obtained from the grain, including its colour as a sensory property (Suzuki et al., 2020; Rakić et al., 2024). Lipid degradation negatively affects taste, which reduces the useful value of the grain and its shelf life (McGorin, 2019). In the meat industry, long-term storage and high temperature negatively affect the sensory and physicochemical characteristics of meat products due to accelerated proteolysis, glycolysis or hydrolytic and oxidative processes in adipose tissue.

Many papers have presented the influence of storage conditions, such as temperature variations and extended storage duration, on the colour change of flour and grains in various cereals, as well as in various types of meat and meat products. It is known that colour changes provide information about the degree of browning-darkening reactions (the Maillard reaction, pigment degradation, caramelization, etc.) or lipid degradation and oxidation, which are mostly, but not always, caused by thermal processes (Anberbir et al., 2023; Atambayeva et al., 2023; Pisinov et al., 2025a). Some studies have shown that up to 80% of consumer decisions are influenced by colour, and 93% of customers reported that colour (visual appearance) is a primary aspect of their purchasing decisions (Khandelwal et al., 2024). Buckwheat-enriched meat products, besides a favourable nutritional profile, may exhibit altered sensory features, specifically color, that reduce the quality attributes of overall acceptability for consumers (Pietrzak et al., 2022). These colour changes can be even more pronounced when green-coloured buckwheat flour is used in the production of thermally processed emulsion-type sausages (Wagh et al., 2015; Lee et al., 2018; Atambayeva et al., 2023; Yessengazyeva et al., 2023).

The aim was to monitor the instrumental colour changes (L^* , a^* , b^* , C^* , h , S and ΔE) of produced composite (enriched) product after adding buckwheat flour obtained from buckwheat stored for 0, 3, 6 and 9 months into emulsion-type chicken sausages.

MATERIAL AND METHODS

Preparation of Buckwheat Flour and Production of Composite Product

Buckwheat (Novosadska variety) used in this research, locally important as an alternative crop and pseudocereal, was harvested in 2022 at technological grain maturity. Raw grains are cleaned of impurities and damaged grains. Sampling was carried out according to the ISO 24333 (2009) method, at 8 locations at an interval of 30 days, forming a representative amount of 4 kg of buckwheat grain sample (approximately 0.5 kg from each of the 8 sampling locations). In the laboratory, the grains were evenly distributed into eight samples, six of which were stored in plastic containers for 3, 6 and 9 months in a drying oven (Digitheat-TFT, J.P Selecta, Barcelona, Spain) at a temperature of $(40 \pm 2)^\circ\text{C}$ with controlled thermoregulation and a relative humidity of 50%. At the end of each testing period, a subsample (approximately 0.5 kg) was formed from the two samples, which were crushed and ground in a laboratory mill A10 (IKA Works Inc., NC, Wilmington, USA) at a speed of 20000 rpm, obtaining wholegrain flour of particle size 1 mm. Further, buckwheat flour was used in the production of a composite product vacuum-packed emulsion-type chicken sausages enriched with stored buckwheat.

Emulsion-type chicken sausages were prepared in a meat processing plant “Milan” located in Dobanovci, Belgrade, which specializes in the processing and sale of chicken meat and products. Five sausage treatments were prepared, each in batches of 2 kg, with the formulations shown in Table 1.

Table 1. Composite product formulations (kg)

Composition (kg)/Group	CON	FB0	FB3	FB6	FB9
Mechanically separated meat	1.13	1.07	1.07	1.07	1.07
Buckwheat flour	/	0.06	0.06	0.06	0.06
Chicken skin	0.38	0.38	0.38	0.38	0.38
Ice	0.38	0.38	0.38	0.38	0.38
Ingredients	0.11	0.11	0.11	0.11	0.11

Ingredients: 2.00% potato starch, 1.80% salt (with 0.5% NaNO₂), 0.85% seasoning, 0.80% beef protein, 0.30% stabilizer - complete, 0.10% carrageenan, and 0.01% colour (E120)

The production process was common for industrial production and identical for all treatments. All formulations contain equal amounts of ingredients, except for the added buckwheat flour. The control treatment (CON) was made from mechanically separated chicken meat (MSM) without the addition of buckwheat flour, while in the other treatments was added buckwheat flour stored for 0 (FB0), 3 (FB3), 6 (FB6) and 9 (FB9) months. After production, control and buckwheat-enriched emulsion-type chicken sausages were vacuum packed (with 99.9% vacuum level) and stored at (2 ± 2) °C. Three repetitions of the experiment were conducted.

Instrumental Color of the Composite Product

Instrumental color was measured at five opposite points of the longitudinal section on each emulsion-type chicken sausage without and with the addition of buckwheat flour on a chromameter CR-400 (Konica Minolta Sensing Inc., Osaka, Japan). Conditions were described by Stajić et al. (2014). The results were expressed in the CIEL*a*b* system (CIE, 1976) following the explanations and formulas described by Pisinov et al. (2025a). The chromameter was calibrated before measurement against a white tile standard ($L^* = +97.83$, $a^* = -0.43$, $b^* = +1.98$). The appearance and colour of composite products, emulsion-type chicken sausage without (control) and with added buckwheat flour stored for 0, 3, 6 and 9 months are presented in Figure 1.

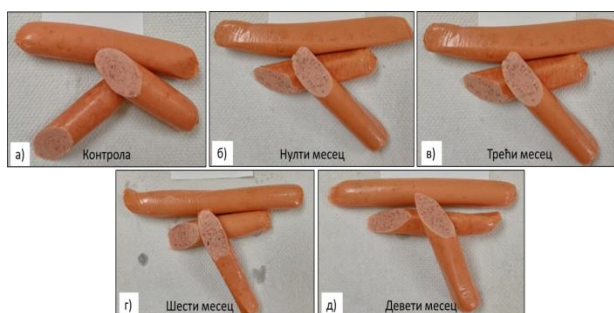


Figure 1. Appearance and colour of composite products (emulsion-type chicken sausage) without (control, (a)) and with added buckwheat flour stored for 0 months (b), 3 months (c), 6 months (d) and 9 months (e).

Statistical Analysis

To interpret the results of the instrumental colour of the composite product, the obtained data are presented as the mean $\pm$ standard deviation ($M \pm SD$). The results of the instrumental colour parameters were statistically processed by one-factor analysis of variance (one-way ANOVA, $p < 0.05$) to assess the influence of the composite product formulation and Tukey HSD (Honestly Significant Difference, $p < 0.05$) post-hoc test to determine differences between mean values. Statistical analysis was performed using Statistica 12.5 software (StatSoft, Inc., Tulsa, OK, USA).

RESULTS AND DISCUSSION

Table 2 shows the values of instrumental colour parameters in relation to different composite products enriched with stored buckwheat. Different formulations of the same type of product significantly affected all instrumental colour parameters ($p < 0.05$). Compared to the CON product, the storage period of buckwheat did not affect L^* values ($p > 0.05$). However, emulsion-type chicken sausage with 0 months of stored buckwheat flour (FB0) is significantly lighter compared to other composite products. This difference in lightness (darkening) is associated with stored buckwheat grains (flour), as the development of lipid oxidation and Maillard reaction products easily occurs during thermally assisted long-term storage and drying (Pietrzak et al., 2022; Pisinov et al., 2024). Similar to our results, Salejda et al. (2022) found that the addition of 3% and more buckwheat husks in frankfurter-type sausages resulted in a decrease in L^* values. Yessengazyeva et al. (2023) noticed that the addition of 12% and more buckwheat flour in semi-smoked sausages made composite product colour unsatisfactorily desirable and more unattractive.

Table 2. Changes in instrumental colour parameters of composite products in relation to the storage period of buckwheat flour added to emulsion-type chicken sausages

Parameters	Product type				
	CON	FB0	FB3	FB6	FB9
L^*	59.25 $\pm$ 0.499 ^{ab}	60.65 $\pm$ 0.467 ^b	58.70 $\pm$ 0.091 ^a	58.95 $\pm$ 0.523 ^a	58.39 $\pm$ 0.876 ^a
a^*	19.07 $\pm$ 0.316 ^c	18.57 $\pm$ 0.190 ^c	15.86 $\pm$ 0.092 ^b	15.09 $\pm$ 0.361 ^a	14.50 $\pm$ 0.170 ^a
b^*	16.48 $\pm$ 0.454 ^b	16.25 $\pm$ 0.212 ^b	15.22 $\pm$ 0.127 ^a	14.96 $\pm$ 0.285 ^a	14.71 $\pm$ 0.112 ^a
C^*	25.21 $\pm$ 0.537 ^c	24.67 $\pm$ 0.275 ^c	21.98 $\pm$ 0.147 ^b	21.25 $\pm$ 0.456 ^{ab}	20.65 $\pm$ 0.193 ^a
h	40.83 $\pm$ 0.307 ^a	41.18 $\pm$ 0.159 ^a	43.82 $\pm$ 0.101 ^b	44.75 $\pm$ 0.139 ^c	45.40 $\pm$ 0.157 ^d
S	39.14 $\pm$ 0.826 ^d	37.68 $\pm$ 0.304 ^c	35.06 $\pm$ 0.181 ^b	33.91 $\pm$ 0.647 ^{ab}	33.35 $\pm$ 0.259 ^a
ΔE	-	1.53 $\pm$ 0.923 ^a	3.53 $\pm$ 0.365 ^b	4.29 $\pm$ 0.198 ^{bc}	5.08 $\pm$ 0.419 ^c

^{a, b, c, d} Means within the same row with different superscripts differ significantly ($p < 0.05$); Emulsion-type chicken sausages: CON: without buckwheat flour; FB0: 3% of buckwheat flour at 0 months of storage; FB3: 3% of buckwheat flour at 3 months of storage; FB6: 3% of buckwheat flour at 6 months of storage; FB9: 3% of buckwheat flour at 9 months of storage

Compared to the CON product, significant differences were noted in the a^* and b^* values of FB sausages. By adding stored buckwheat grains (flour), the red and yellow tones of sausages are progressively reduced. These decreasing trends can be explained by the loss

of phenolic compounds as natural pigments, which is even more pronounced during thermally assisted long-term storage and drying (Kilincceker and Karahan, 2020; Pisinov et al., 2024). Our results were in agreement with the findings of Kilincceker and Karahan (2020), who found that added buckwheat flour caused a decrease in redness and yellowness of fried chicken meatballs.

Significantly lower C^* values were found in FB3, FB6 and FB9 sausages. The long-term stored buckwheat flour included in the formulation resulted in FB9 sausages had lower chromatic purity, showing the shortest distance from lightness compared to other sausages. For *hue* angle (h) values between CON and FB0 did not differ significantly, but the significance increased with FB3, FB6 and FB9. The addition of buckwheat grains (flour) stored for 0 to 9 months led to a progressive increase in the proportion of yellow nuance in sausages. Cavalheiro et al. (2013) stated that C^* and h values depend on a^* and b^* values, and changes in these values are caused by the same reasons as those in a^* and b^* . The progressive loss of phenolic compounds is more pronounced as the storage time of buckwheat increases from 0 to 9 months, leading to a less saturated appearance of sausages, as the a^* and b^* values decrease and cause changes from red to yellow colour due to a more pronounced decrease in a^* than in b^* values. Varga-Visi et al. (2021) came to the same conclusion by examining sausage with paprika, where the changes in colour were attributed to the deterioration of the chromophores in meat and paprika, i.e. the decomposition of those pigments.

The S values of all emulsion-type chicken sausages differ significantly compared to CON. By adding long-term stored flour to the formulation, a decreasing trend of saturation was observed, which became more pronounced with longer storage. As the S value is derived from the L^* and C^* values, their reduction by incorporating long-term stored flour into the formulation directly causes a trend of decreasing S values from CON to FB9, for the same reasons as for L^* and C^* .

Furthermore, the total colour difference (ΔE) values gradually increased with the addition of longer-stored flour to the formulation. Variations in the L^* , a^* and b^* parameters of sausages made from differently stored flour affected the total colour difference parameter (ΔE). This means that, compared to CON, the highest degree of colour change was observed for FB9. It is known that ΔE values < 2.0 indicate a colour difference compared to the control that the human eye cannot detect. In contrast to our results, Pietrzak et al. (2022) reported that there was no significant difference in ΔE values when testing the effect of buckwheat hull extracts on the quality of chicken meatballs.

CONCLUSION

The obtained results indicate that it is possible to use long-term stored buckwheat grains (flour) for up to 9 months without significantly impairing the visual properties of the final product. Colorimetric analysis of L^* , a^* , b^* , C^* , h , S and ΔE indicates that colour changes remain within the range sensory acceptable to consumers, and the optimal proportion of buckwheat flour in the formulation of products such as vacuum-packed emulsion-type chicken sausages is 3%. In this way, the meat industry is provided with reliable guidelines for the rational use of plant-based functional raw materials such as buckwheat in the development of products with improved colour-sensory properties.

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STATISTICAL MODELING AND PREDICTION OF THE INFLUENCE OF STORED BUCKWHEAT ON THE COLOR OF THE FINAL PRODUCT

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Abstract: Incorporating plant-based ingredients into meat products faces challenges regarding raw material stability and its impact on sensory quality. This study aimed to apply multivariate statistical analysis to map the interdependency between the degradation of bioactive compounds in stored buckwheat flour and the color change of emulsion-type chicken sausages. Buckwheat flour was stored for 0, 3, 6, and 9 months at 40 °C and incorporated (3%) into sausage formulations. The relationship between flour antioxidant parameters (TPC, FRAP, individual phenolics) and sausage instrumental color was analyzed using Pearson's correlation, Principal Component Analysis (PCA), and Linear Regression. Results indicate that storage causes a drastic drop in antioxidant power (FRAP decreased 2.9-fold) and epicatechin degradation. A strong positive correlation was established between flour FRAP values and sausage redness (a^* , $r=0.984$). PCA confirmed clear differentiation between fresh and aged samples based on oxidative status. The linear regression model predicted redness with high apparent precision ($R^2=0.969$), though residual analysis (RMSE=0.274) revealed non-linear deviations. In conclusion, the antioxidant power of the raw material is a critical predictor of final product color. While linear models provide high accuracy, future research should consider non-linear algorithms to fully address complex matrix interactions.

Keywords: Buckwheat flour, Emulsion sausages, Antioxidant power, Instrumental color, Multivariate analysis, Prediction

INTRODUCTION

Growing consumer awareness regarding the relationship between diet and health has led to a global increase in demand for functional food products (Grasso et al., 2014; Bigliardi and Galati, 2013). The meat industry faces significant challenges regarding consumer perception, as meat products are often associated with negative health effects due to high saturated fat and synthetic additive content (Decker and Park, 2010; Zhang et al., 2010). In response to these challenges, the reformulation of meat products through the addition of plant-based ingredients has become a leading strategy for improving their nutritional profile and oxidative stability (Jiménez-Colmenero, 2007; Petracci et al., 2013).

Among potential functional additives, buckwheat (*Fagopyrum esculentum* Moench) occupies a prominent place due to its exceptional chemical composition. Buckwheat is a

gluten-free pseudocereal characterized by a high content of proteins with a balanced amino acid profile, as well as an abundance of dietary fibers and minerals (Christa and Soral-Śmietana, 2008; Wijngaard and Arendt, 2006). From a technological aspect, buckwheat phenolic compounds, primarily rutin, quercetin, and catechin, are of particular importance due to their potent antioxidant potential (Giménez-Bastida and Zieliński, 2015; Jiang et al., 2007; Holasova et al., 2002). Previous studies have confirmed that the incorporation of buckwheat flour or hulls into meat emulsions can effectively retard lipid peroxidation and improve product shelf life (Hęś et al., 2017; Belem et al., 2019; Salejda et al., 2022).

Nevertheless, the use of plant-based raw materials in the meat industry implies certain limitations, primarily related to stability during storage. It is known that degradative changes occur during the storage of grains and flour, including lipid hydrolysis and enzymatic degradation of phenolic compounds (Rakić et al., 2023; Pisinov et al., 2024; Sedej et al., 2010; Zieliński et al., 2019). Studies have shown that the content of rutin and other flavonoids decreases significantly over time due to environmental factors, directly diminishing the functional value of the raw material (Lukšič et al., 2016; Suzuki et al., 2020).

These changes in the raw material have direct implications for the sensory quality of the final product, with color being the most critical parameter. Meat color is the primary attribute by which consumers judge freshness, and myoglobin oxidation to metmyoglobin leads to the appearance of an undesirable brown color (Mancini and Hunt, 2005; Faustman and Cassens, 1990; Suman and Joseph, 2013). Although it has been established that the addition of buckwheat modifies the colorimetric parameters of sausages (Pisinov et al., 2025; Rakić et al., 2024; Yessengazyeva et al., 2023; Sol-Hee et al., 2018), a precise quantification of the impact of the degradation of specific bioactive compounds in stored buckwheat on the color change of the final product is lacking.

Analyzing such complex interdependencies in food matrices requires the application of advanced statistical methods. Traditional linear approaches, such as Multiple Linear Regression (MLR), are often inadequate for modeling non-linear interactions between physico-chemical parameters of different dimensions (Perrot et al., 2006; Barbin et al., 2015). As shown in earlier studies on complex systems by Sekulić et al. (2019), reliable prediction of output parameters in non-linear processes requires the use of advanced multivariate techniques and models based on artificial intelligence, which generally outperform conventional regression models.

The aim of this study is to apply a multivariate approach (PCA and correlation analysis) to map the relationship between the degradation of nutritional and antioxidant parameters of stored buckwheat flour and the instrumental color change of emulsion-type chicken sausages, thereby defining key predictors for future robust modeling.

MATERIAL AND METHODS

Experimental Design and Database Formation

The data used for multivariate analysis in this study were obtained through a controlled experiment involving raw material storage and subsequent meat product manufacturing.

Buckwheat (*Fagopyrum esculentum Moench*), variety "Novosadska", grown and harvested in the 2022 season, was subjected to an accelerated storage treatment. Grain samples were stored in thermostatic chambers at a temperature of 40 ± 2 °C and a relative humidity of 50% for four-time intervals: 0, 3, 6, and 9 months. After each interval, the grains were ground into integral flour (particle size < 1 mm) according to the procedure detailed in the study by Rakić et al. (2023).

The prepared flour was used as a functional additive in the production of emulsion-type chicken sausages (frankfurter type). Five experimental groups were produced: a control group (CON) without buckwheat addition, and four groups with 3% added buckwheat flour previously stored for 0, 3, 6, and 9 months (labeled as FB0, FB3, FB6, and FB9). The formulations were iso-protein and iso-energetic, with identical proportions of other ingredients (mechanically separated meat, ice, additives), applying standard industrial technology described by Pisinov et al. (2025).

For the purposes of this research, a unique dataset was formed where each row represents the mean measurement value for a specific time treatment, and columns represent physico-chemical parameters (variables).

Table 1. Definition of input and output variables for multivariate statistical analysis

Vector Type	Parameter Group	Parameter (Variable)	Unit	Method / Reference
INPUT (X)	Chemical Composition	Moisture	%	ISO 712
		Protein	% DM	ISO 20483
		Lipids	% DM	NMKL 160
		pH value	-	AOAC 943.02
INPUT (X)	Antioxidants	TPC (Total Phenols)	mg GAE/g	Folin-Ciocalteu
		FRAP	μmol Fe ²⁺ /g	Spectrophotometry
		DPPH	μmol TE/g	Spectrophotometry
INPUT (X)	Phenolic Profile	Epicatechin	μg/g DM	HPLC-PDA
		Chlorogenic acid	μg/g DM	HPLC-PDA
		Quercetin	μg/g DM	HPLC-PDA
INPUT (X)	Flour Colour	L [*] _{flour} , a [*] _{flour} , b [*] _{flour}	CIE system	Chromameter (CR-410)
OUTPUT (Y)	Sausage Colour	Lsausage*, asausage* bsausage*	CIE system	Chromameter (CR-400)
		C*(Chroma), h (Hue)	-	Calculated
		ΔE (Total difference)	-	Calculated

Laboratory Analysis (Input and Output Variables)

Laboratory analyses were conducted according to standard international methods.

Input vectors (X) include quality parameters of buckwheat flour:

- Chemical composition: Moisture content (ISO 712), protein (ISO 20483), lipids (NMKL 160), total carbohydrates, and pH value,

- Antioxidant profile: Total phenolic content (TPC) determined by the Folin-Ciocalteu method, antioxidant power (FRAP), and radical scavenging activity (DPPH),
- Phenolic profile: Content of specific phenolic acids (gallic, chlorogenic, caffeic, p-coumaric, ferulic) and flavonoids (catechin, epicatechin, rutin, quercetin) was determined using the HPLC-PDA method according to the protocol defined by Pisinov et al. (2024),
- Instrumental flour color: Parameters L^* (lightness), a^* (redness), and b^* (yellowness) were measured using a chromameter (CIE Lab* system, D-65 illuminant) in accordance with previous research on the same plant material (Rakić et al., 2024).

Output vectors (Y): Include color parameters of the final product (sausage):

- Measured values L^* , a^* , b^* , as well as derived colorimetric parameters: chroma (C^*), hue angle (h), and total color difference (ΔE) relative to the control sample.

Statistical Processing and Modeling

Given the different units of measurement and ranges of input parameter values, all data were normalized (Z-score normalization) prior to processing to eliminate the influence of different dimensions on multivariate analysis results. All statistical analyses were conducted using the software package IBM SPSS Statistics for Windows, Version 26.0 (IBM Corp., Armonk, NY, USA).

The data processing procedure included the following steps:

- **Correlation Analysis.** Interdependency between buckwheat degradation variables and sausage color changes was examined using Pearson's correlation coefficient (r). Statistical significance of correlations was tested at the level of $p < 0.05$. Results are presented in the form of a correlation matrix (heatmap) for easier visualization of relationship strength and direction,
- **Principal Component Analysis (PCA).** As a robust chemometric method for dimensionality reduction and pattern detection in food systems (Granato et al., 2014), PCA was applied to the correlation matrix. The number of significant principal components was determined based on the Kaiser criterion (eigenvalue > 1) and the "Scree plot",
- **Regression Modeling.** To quantify predictive potential, Simple Linear Regression was used.

A detailed schematic representation of the entire statistical analysis flow, from data preparation to model validation, is illustrated in Figure 1.

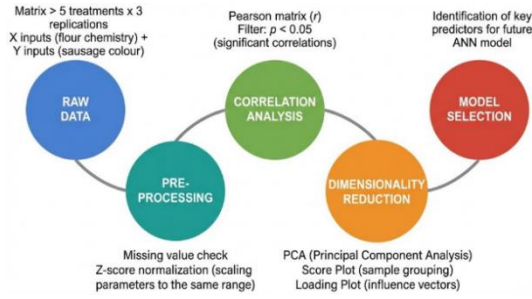


Figure 1. Schematic representation of experimental design and statistical data processing flow

Criteria for Evaluating Prediction Success

To quantify the strength of the relationship between input parameters (flour quality) and output variables (sausage color), and to estimate the predictive potential of the defined statistical models, standard statistical error indicators were used, according to methodology previously applied in complex non-linear systems (Sekulić et al., 2019).

Model success was evaluated by calculating the Coefficient of Determination (R^2), which shows the percentage of variance explained by the model, as well as error metrics, Root Mean Square Error (RMSE) and Mean Absolute Error (MAE) (Barbin et al., 2015).

These parameters were calculated according to the following equations:

$$R^2 = 1 - \frac{\sum_{i=1}^n (y_{obs,i} - y_{pred,i})^2}{\sum_{i=1}^n (y_{obs,i} - \bar{y}_{obs,i})^2} \quad (1)$$

$$RMSE = \sqrt{\frac{1}{n} \sum_{i=1}^n (y_{pred,i} - y_{obs,i})^2} \quad (2)$$

$$MAE = \frac{1}{n} \sum_{i=1}^n |O_i - P_i| \quad (3)$$

Where:

n - total number of samples in the dataset,

$y_{pred,i}$ - predicted value of the output parameter (based on the regression model),

$y_{obs,i}$ - experimentally measured (observed) value,

$\bar{y}_{obs,i}$ - mean value of all experimental measurements.

According to criteria accepted in predictive microbiology and food technology, higher R^2 values (tending towards 1), as well as lower RMSE and MAE values (tending towards 0), indicate greater model precision and more reliable prediction capability for the final product quality (Granato et al., 2014).

RESULTS AND DISCUSSION

Overview of Matrix Degradation and Parameter Variability

Before conducting multivariate analysis, descriptive statistics were applied to examine trends in input and output vectors and confirm the variability necessary for modeling. A summary of key chemical parameters of the raw material and colorimetric properties of the final product, expressed as mean values, is given in Table 2.

Raw material analysis confirmed that the storage process at 40 °C significantly alters the chemical profile of buckwheat flour ($p < 0.05$). A drastic drop in antioxidant power was observed, with the FRAP value decreasing by approximately 2.9 times (from 63.45 to 22.20 $\mu\text{mol Fe}^{2+}/\text{g DM}$) over 9 months. This trend was accompanied by a specific redistribution of phenolic compounds: while potent antioxidants like epicatechin significantly degraded, quercetin content paradoxically increased, likely due to release from glycosidic bonds or hydrolytic processes during storage.

Table 2. Changes in selected chemical parameters of buckwheat flour and sausage color parameters during the storage period (mean values only)

Storage Time	Flour FRAP ($\mu\text{mol Fe}^{2+}/\text{g CM}$)	Epicatechin ($\mu\text{g/g DM}$)	Quercetin ($\mu\text{g/g DM}$)	Sausage a^* (Redness)	Sausage ΔE (Total difference)
0 months (FB0)	63.45	95.7	9.8	18.57	1.53
3 months (FB3)	28.68	78.5	12.5	15.86	3.53
6 months (FB6)	25.32	77	16.6	15.09	4.29
9 months (FB9)	22.2	59.8	47.1	14.5	5.08

As seen from these data, chemical changes in the raw material resulted in measurable variations in the final product. Chicken sausages produced with aged flour showed a progressive loss of characteristic redness, where the a^* value dropped from 18.57 (FB0) to 14.2 (FB9). Simultaneously, the total color difference (ΔE) reached a value of 5.08, clearly exceeding the threshold for consumer sensory detection. This dataset, with clearly expressed but opposing trends (decrease in FRAP and epicatechin versus increase in quercetin and ΔE), represents a valid basis for further correlation modeling.

Correlation Analysis of Interdependencies (Pearson Matrix)

To quantify the strength and direction of the relationship between chemical changes in flour and the sensory quality of the sausage, Pearson's correlation matrix (r) was calculated. The results of cross-referencing key raw material parameters and the final product are displayed in Table 3, visualized using a color scale ("heatmap") to facilitate pattern identification.

Table 3. Pearson correlation matrix (r) between flour quality parameters (inputs) and sausage color parameters (outputs)

	Sausage L* (Lightness)	Sausage a* (Redness)	Sausage b* (Yellowness)	Sausage ΔE (Total change)
TPC (Total Phenols)	0.824	0.874	0.855	-0.869
FRAP (Antioxidant power)	0.851	0.984	0.912	-0.978
Epicatechin	0.795	0.930	0.880	-0.925
Quercetin	-0.810	-0.895	-0.860	0.910

Note: Values are displayed on a "Heatmap" color scale: intense red ("hot") indicates a strong positive relationship (values closer to +1), while intense blue ("cold") indicates a strong negative relationship (values closer to -1).

Analysis of the "heatmap" immediately reveals key zones of influence. A zone of distinctively "hot" (red) correlation dominates between the antioxidant parameters of the raw material and the redness parameter of the final product. The strongest positive correlation in the entire matrix was observed between the antioxidant power of the flour (FRAP) and the redness of the sausage (a^*), with a coefficient of $r = 0.984$. This implies an almost functional dependence: the preservation of the flour's reducing ability directly dictates the intensity of the red color in the product. The high statistical reliability of this link confirms the mechanism by which buckwheat phenols protect myoglobin from oxidation.

On the other hand, the total color change column (ΔE) shows strong "cold" (blue) correlations with antioxidants, particularly with the FRAP value ($r = -0.978$). The negative sign indicates an inverse proportion: the lower the antioxidant protection of the flour, the greater (worse) the color change of the sausage. An interesting exception is quercetin, whose row in the table shows an inverse color arrangement compared to other antioxidants. It shows a strong negative relationship with redness ($r = -0.895$) and a positive relationship with ΔE ($r = 0.910$). This confirms that quercetin accumulation during storage can be viewed as a reliable chemical indicator (marker) of aging that indicates the degradation of colorimetric properties.

Principal Component Analysis (PCA)

Before interpreting PCA components, the suitability of the dataset for factorization was checked. The Kaiser-Meyer-Olkin (KMO) measure of sampling adequacy was 0.72, which is above the recommended threshold of 0.5. Additionally, Bartlett's test of sphericity showed statistical significance ($p < 0.001$), justifying the application of PCA analysis to this dataset.

Multivariate analysis enabled dimensionality reduction and detection of mutual relationships between variables, with the first principal component (PC1) clearly defined as the "oxidative status axis". Geometric arrangement of vectors in Figure 2 reveals key structural laws in the data, primarily observing a distinct grouping of variables FRAP, TPC, Epicatechin, and redness (a^*) in the right part of the graph (positive PC1 axis). The proximity and directionality of these vectors in the same direction confirm that high antioxidant power of the raw material directly supports the preservation of redness.

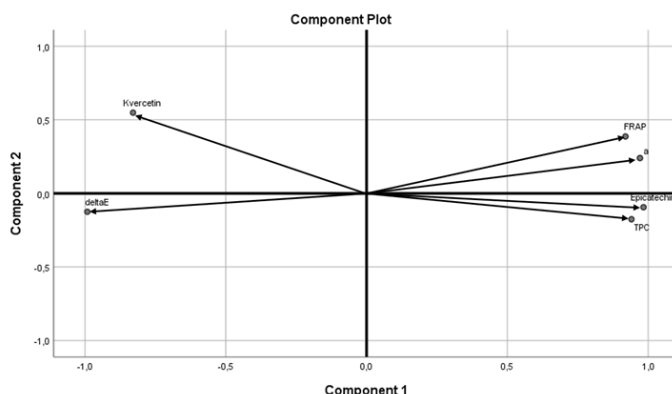


Figure 2. Component Plot in Rotated Space obtained by SPSS analysis, showing vector relationships and grouping of examined variables

In contrast, the total color change vector (ΔE) is isolated on the opposite, left side of the graph, visually demonstrating a strong inverse correlation with antioxidants. Additionally, the Quercetin vector occupies a specific position in the upper left quadrant, separated from the primary group of antioxidants, indicating its role as a specific marker of matrix degradation that behaves differently during the storage process.

Regression Model Evaluation and Limitations

Based on the established high correlations, a Linear Regression procedure (SPSS Linear Regression) was applied to form a predictive model for sausage redness (a^*) based on flour FRAP value. The statistical reliability of the model was confirmed by Fisher's F-test (ANOVA), which showed high regression significance ($F = 62.53$, $p = 0.016$), thereby rejecting the null hypothesis of no linear relationship.

The obtained model equation is:

$$a_{pred}^* = 0.092 * FRAP + 12.787 \quad (4)$$

Quantitative indicators of this model's success are summarized in Table 4.

Table 4. Parameters and performance of the developed linear regression model

Input Variable (x)	Output Variable (y)	Model Equation	R ²	RMSE	MAE
FRAP ($\mu\text{mol Fe}^{2+}/\text{g}$)	Sausage a^* (CIE redness)	$y=0.092x+12.787$	0.969	0.274	0.215

The graphical fit of experimental data with predicted values is shown in Figure 4. Visual inspection of the diagram confirms a high degree of linearity, where experimental points (markers) closely follow the regression line, especially in zones of fresh (FB0) and long-term stored raw material (FB9).

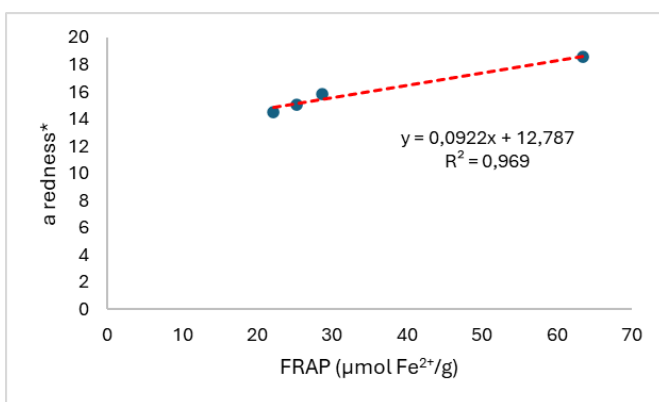


Figure 3. Linear regression model of the dependence of parameter a^* on FRAP value

In contrast, a more detailed residual analysis reveals limitations of this approach. Although R^2 is high, the presence of detected error (RMSE = 0.274) suggests that there are deviations that cannot be ignored in the context of precise standardization. Linear models are limited when describing complex biological systems where opposing mechanisms act simultaneously. These results suggest a clear room for improving prediction accuracy by applying more sophisticated, non-linear artificial intelligence algorithms (ANN) in future research.

CONCLUSION

This study applied multivariate statistical analysis for the first time to map the interdependency between the degradation of bioactive compounds in stored buckwheat flour and the color change of emulsion-type chicken sausages.

Based on the results obtained, the following conclusions are drawn:

- **Matrix Degradation:** The buckwheat storage process leads to significant chemical changes ($p < 0.05$), with the most critical being the loss of antioxidant power (FRAP value decrease by 2.9 times) and degradation of specific phenols such as epicatechin. These changes in the raw material directly correlate with the loss of characteristic redness in the final product,
- **Key Predictors:** Correlation and PCA analysis identified the FRAP value of flour as the most reliable single marker ($r = 0.984$) for predicting the colorimetric quality of the sausage. This confirms that preserving the reducing ability of the additive is a key mechanism for preventing meat pigment oxidation,
- **Model Reliability:** The developed linear regression model showed high precision ($R^2 = 0.969$) and statistical significance ($F = 62.53$, $p = 0.016$), providing the industry with a simple and fast tool for estimating expected product color based on input raw material analysis, prior to the start of the production process,
- **Guidelines for Future Research:** Despite the high coefficient of determination, the detected residual error (RMSE = 0.274) and mean absolute error (MAE = 0.215) indicate the limitations of the linear approach in describing complex interactions within the food matrix.

Final conclusion of this research is that statistical modeling can successfully link raw material and product quality, but complete elimination of error requires the application of more sophisticated algorithms. The next phase of research will focus on developing models based on Artificial Neural Networks (ANN), aiming to further improve prediction precision for robust standardization of functional meat products.

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REDUCED IRRIGATION NORM AS A SUSTAINABLE AGROTECHNICAL MEASURE IN SWEET CORN PRODUCTION

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Abstract: The reduced norm of irrigation (50%) compared to the full (100%) and control was tested in three sweet corn hybrids (Enterprise, Union, and Sweet Nugget) in two sowing dates. Irrigation deficit did not significantly affect plant height, height to first ear or number of leaves in Enterprise and Union hybrids. Sweet Nugget had lower values of all parameters. ANOVA showed significant effects of irrigation, genotype, sowing date, and their interactions on most traits. The reduced rate enables 50% water savings without affecting plant morphology.

Keywords: Sweet corn, Reduced irrigation, Morphological characteristics, Hybrids, Date of sowing, Water saving

INTRODUCTION

Modern agricultural production faces increasingly pronounced challenges of climate change (Stojiljković et al., 2025), reduced availability of water resources (Ćosić et al., 2018; Moravčević et al., 2021), and the need to preserve the environment (Šević et al., 2025). Sweet corn (*Zea mays* L. var. *saccharata*), a crop of high market value and high-water demand during critical stages of development, is a good choice for testing the feasibility of applying reduced irrigation norms without a significant decrease in grain yield and quality. The morphological characteristics of the plant - the height of the plant, the height of the plant to the first ear, and the number of leaves per plant directly reflect the degree of adaptation of genotypes to moisture deficit and are reliable indicators of photosynthetic potential and yield stability (Moteva et al., 2016; Nemeskéri, 2019). Numerous studies have shown that the full norm of irrigation significantly increases plant height (up to 22%) and the number of leaves (up to 45.3%) compared to production in conditions without watering (Moteva et al., 2016), while deficit irrigation or its absence leads to a decrease in these parameters (Nemeskéri, 2019; Ugur, 2015). In addition to the irrigation norm, the sowing date significantly affects sweet corn development (Shibzukhov et al., 2021; Tupajić et al., 2024). Earlier sowing dates (end of April) result in greater plant height due to a more favourable distribution of precipitation in May and June (Soare, 2019), whereas delaying sowing usually leads to a decrease in plant height and the position of the first ear (Ugur, 2015; Kilinç, 2021). Leaves, especially those around the ear, play an important role in yield formation (contribution of about 15% of total photosynthesis - Fujita

et al., 2001), and their surface, number and duration of green colour are directly related to the water and nitrogen regime (Zhou et al., 2019; Đalović et al., 2021).

The research aimed to examine the impact of a reduced irrigation rate (50% of the full rate) on the morphological characteristics of sweet corn in order to promote sustainable agriculture.

Working hypothesis: applying a reduced irrigation norm will not negatively affect the studied morphological features, enabling a 50% reduction in water consumption. This hypothesis represents an innovative step towards sustainable production in conditions of climate change.

MATERIAL AND METHODS

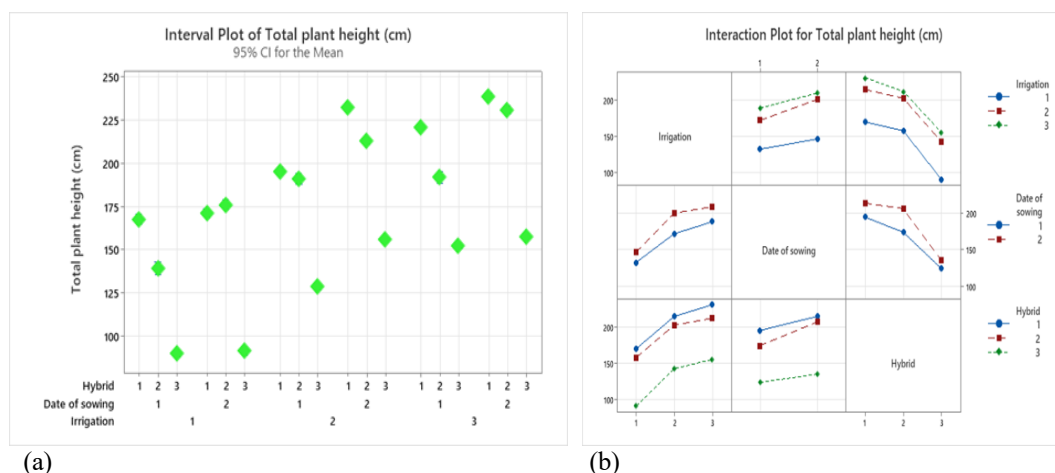
The experiment was carried out in 2022 and 2023 in the village of Bresje, the municipality of Velika Plana, the Podunavski District, Serbia. Sweet corn was grown using standard agrotechnical measures. The sowing density was about 65.000 plants per hectare (distance between rows 70 cm and between plants 22 cm). The experiment was set up in a completely randomised block design with four replications and the following factors: irrigation norm, genotype, and sowing date.

Irrigation was carried out with a drip system with strips with a capacity of 10 l•m⁻¹•h, placed between the rows. The applications were: (1) full norm (100%) - calculated by the formula; (2) reduced norm (50%) - half of the full norm; (3) control - in the conditions of the natural wetting regime. The soil samples were analyzed in the Soil Reclamation Laboratory at the Faculty of Agriculture in Zemun. Soil moisture was monitored by tensiometers at a depth of 0.3 m at full irrigation rate. During the vegetation period, soil moisture was maintained at 60% PVK using tensiometers, which were read every 3-4 days to calculate the watering rate. The watering norm is calculated according to the formula: $N_z = 10 \times D \times (PVK\% \text{ vol} - \theta_z)$ (mm/m²), where D is the depth of the layer, PVK% vol is the hydrolimit of the field's water capacity in per cent by volume, and θ_z is the measured humidity. In the experiment, there were isolation belts (buffers) between treatments.

Plant material: 3 genotypes of sweet corn (1) Enterprise F1 - standard sweetness, vegetation 85 days, tall plants; (2) Union F1 - three-line hybrid, vegetation 90 days, long ear; (3) Sweet Nugget - super sweet corn hybrid, 65 days of vegetation. Sowing dates: (1) first date - end of April/beginning of May; (2) second date - mid-July, after the wheat harvest. Land preparation included ploughing and preliminary preparation. Total plant height, ear height and number of leaves were measured. The data were analyzed using ANOVA and LSD post hoc tests in IBM SPSS Statistics 26.0, with tabular and graphical displays.

RESULTS AND DISCUSSION

The total plant height of the sweet corn (Figure 1a) varied significantly across genotypes, sowing dates, and irrigation norms. The highest values were recorded for the Enterprise hybrid on the second date of sowing 239.02 cm at the full irrigation norm and 232.38 cm at the reduced norm.



(a) Figure 1a. Interval plot with 95% confidence interval for the average value for the total plant height (cm) in the two years (2022-2023) at different irrigation norms in the two dates of sowing for the tested hybrids; Figure 1b. Interaction plot for the total plant height (cm) and the influence of the observed factors in the two years (2022-2023)

The Union hybrid reached the highest total plant height of 231.13 cm at full norm at the same sowing date, while the Sweet Nugget hybrid was significantly shorter (89.90-157.59 cm) in all treatments. Analysis of variance (Table 1) confirmed highly significant effects ($p < 0.001$) for all investigated factors (irrigation, genotype, date of sowing) and their double and triple interactions (Figure 1b).

Table 1. Analysis of variance for the factors investigated and the significance of their influence on the total plant height

Parameter	Total plant height			
Factor	SS	Sign.	LSD $p < 0.05$	LSD $p < 0.01$
Irrigation	1421956.048	**	1.366	1.795
Date of sowing	240793.400	**	1.115	1.466
Hybrid	2298680.182	**	1.366	1.795
Irrigation x Date of sowing	19470.811	**	1.931	2.539
Irrigation x Hybrid	8918.784	**	2.365	3.109
Date of sowing x Hybrid	42023.875	**	1.931	2.539
Irrigation x Date of sowing x Hybrid	47167.111	**	3.345	4.397
Total	4452925.637			

Legend: SS - sum of squares; Sign.- significance; ** $p < 0.01$; * $p < 0.05$; LSD - Least significant difference test

The obtained results are in agreement with the results of earlier research that the moisture deficit limits the growth of the above-ground part of the plant (Nemeskéri, 2019; Ugur, 2015), but at the same time they show that the reduced irrigation norm in more tolerant hybrids (Enterprise and Union) does not lead to a statistically significant reduction in total plant height, which is of extreme practical importance in conditions of limited water resources.

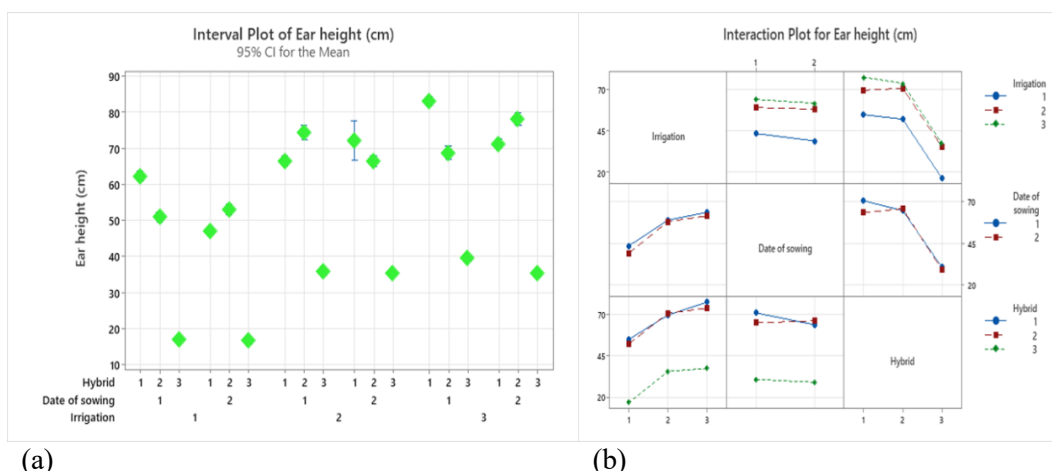


Figure 2a. Interval plot with 95% confidence interval for the average value for the ear height (cm) for the two years at different irrigation norms in the two dates of sowing for the tested hybrids; Figure 2b. Interaction Plot for ear height (cm) and the influence of observed factors in the two years (2022-2023)

Ear height (Figure 2a) ranged from 16.57 cm (Sweet Nugget, control) to 83.04 cm (Enterprise, full norm, first date of sowing). In the Enterprise and Union hybrids, the differences between the full and reduced norms were minimal (71.25-72.13 cm for Enterprise in the second date of sowing), which indicates that the ear height did not change even with the reduced watering norm.

All investigated factors (Table 2) and their interactions (Figure 2b) were statistically significant ($p < 0.01$ or $p < 0.05$), consistent with the findings of Kiliņa (2021) and Anil and Sezer (2003).

Table 2. Analysis of variance for the examined factors and the significance of their influence on ear height

Parameter	Ear height			
Factor	SS	Sign.	LSD $p < 0.05$	LSD $p < 0.01$
Irrigation	187394.045	**	1.043	1.372
Date of sowing	3513.900	**	0.852	1.120
Hybrid	632831.910	**	1.043	1.372
Irrigation x Date of sowing	1185.700	**	1.476	1.940
Irrigation x Hybrid	2571.362	**	1.807	2.376
Date of sowing x Hybrid	6467.609	**	1.476	1.940
Irrigation x Date of sowing x Hybrid	23424.247	**	2.556	3.360
Total	1075672.665			

Legend: SS - sum of squares; Sign.- significance; ** $p < 0.01$; * $p < 0.05$; LSD – Least significant difference test.

The total number of leaves per plant (Figure 3a) was highest in hybrids Union (11.86 at full norm) and Enterprise (11.70 at reduced norm), while Sweet Nugget had between 7.06 and 7.98 leave.

ANOVA showed (Table 3) a significant effect of irrigation ($p < 0.01$), genotype ($p < 0.001$) and the interaction genotype x irrigation ($p < 0.05$), but not the date of sowing or its interaction with irrigation (Figure 3b). The three-way interaction was not statistically significant. These results are in accordance with the observations of Moteva et al. (2016) and Soara (2019) that irrigation increases the number of leaves but show that in selected hybrids the reduced norm does not threaten the formation of leaf mass, thus preserving the photosynthetic potential of the plant (Zhou et al., 2019; Fujita et al., 2001).

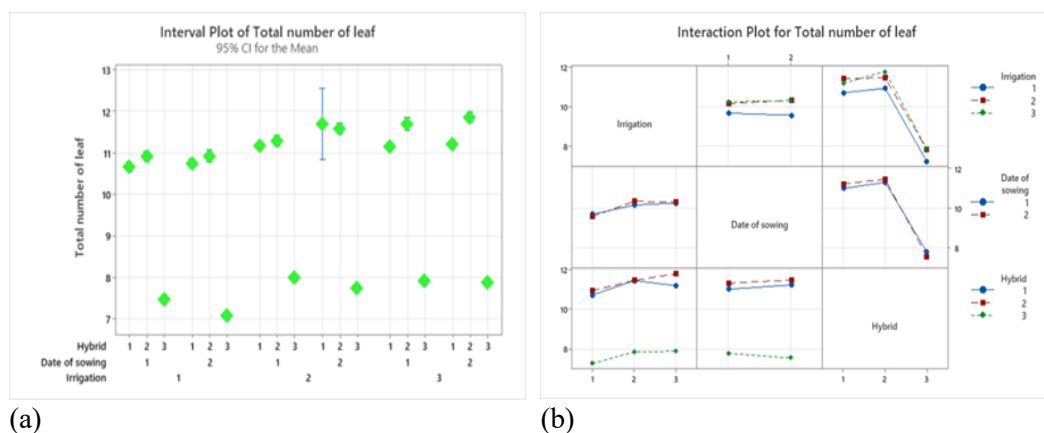


Figure 3a. Interval plot with 95% confidence interval for the average value for the total number of leaves for the two years at different irrigation norm on the two dates of sowing for the investigated hybrid; Figure 3b. Interaction Plot for the total number of leaves and the influence of the observed factors in the two years (2021-2023).

Table 3. Analysis of variance for the factors investigated and the significance of their influence on the total number of leaves

Parameter	Total number of leaves			
Factor	SS	Sign.	L.S.D. (<0.05)	L.S.D. ($p < 0.01$)
Irrigation	193.6549	**	0.131	0.173
Date of sowing	1.300	ns	0.107	0.141
Hybrid	6169.077	**	0.131	0.173
Irrigation x Date of sowing	7.778	ns	0.186	0.244
Irrigation x Hybrid	21.347	*	0.227	0.299
Date of sowing x Hybrid	20.649	**	0.186	0.244
Irrigation x Date of sowing x Hybrid	7.310	ns	0.321	0.423
Total	9874.163			

Legend: SS - sum of squares; Sign.- significance; ** $p < 0.01$; * $p < 0.05$; ns - no significant difference at $p > 0.05$ level, LSD – Least significant difference test.

CONCLUSION

The application of a reduced irrigation norm (50%) proved effective for sweet corn production, without adverse effects on total plant height, ear height, or the number of leaves in the tested genotypes across both sowing dates. This enables a 50% reduction in water consumption, contributing to sustainable resource use. In the context of climate change,

this approach represents an innovation for stable, economical production, with a recommendation for further research on kernel yield and quality.

ACKNOWLEDGMENT

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SPREAD OF INVASIVE PLANT *HERACLEUM SOSNOWSKYI* IN SERBIA

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Abstract: *Heracleum sosnowskyi* is an invasive plant posing serious ecological and health risks in Europe. This study analyzes its biology, toxic properties, invasion history, and rapid spread at the Kovilovo site (Serbia) from 2017-2025. Field surveys and drone monitoring revealed a rapid expansion from a small population to several tens of hectares, highlighting high invasion potential and the urgent need for coordinated control measures.

Keywords: *Heracleum sosnowskyi*, Biodiversity impact, Phototoxicity, Seed dispersal, Serbia, Invasive plant management

INTRODUCTION

Heracleum sosnowskyi is a weedy plant from the family *Apiaceae* (*Umbelliferae*). This is a large family comprising about 3.500 species, whose name stems from the characteristic umbrella-shaped inflorescences. The best-known plants of this family are carrot, celery, parsnip, fennel, anise, caraway, coriander, dill, etc. The medicinal plant angelica also belongs to this family, while the rest are mostly wild species. All species of this family are particularly rich in essential oils and aromatic secondary metabolites that are used in homeopathy, nutrition, folk medicine, and have pharmacological activity. Some plants also contain toxic substances, such as hemlock, wild parsnip, and others (Holub, 1997).

The genus *Heracleum*, as part of the *Apiaceae* family, includes about 400 species and subspecies, most of which live in Asia, where they originated (from the Caucasus Mountains in southwestern Asia and the Hengduan Mountains in southern China). About 20 species of *Heracleum* are present in Europe. From the perspective of their invasiveness and danger to humans (human health) and the environment, the most significant are the following three species: *Heracleum mantegazzianum* Somm. et Levier, *Heracleum sosnowskyi* Manden., and *Heracleum persicum* Desf. These species are classified as so-called "giant" species due to their height (3-5 m) and large leaves (up to 3 m in length, Figure 1), which is why they are often called "giant hogweeds". *Heracleum persicum* has a smaller habitus, while *H. sosnowskyi* and *H. mantegazzianum* are very similar and differ in specific characteristics of the stem and leaves (Jahodova et al., 1997; EPPO, 2020).



Figure 1. Large leaves of *H. sosnowskyi*



Figure 2. *Heracleum sosnowskyi*

Six species of the genus *Heracleum* are present in the flora of Serbia: *H. pallinianum*, *H. sibiricum*, *H. verticillatum*, *H. orphanidis*, and the most widespread *Heracleum sphondylium* subsp. *verticillatum*, commonly known as bear's paw, bear's hand, bear's palm, or bear's foot. This is a native European species used as a medicinal plant; animals readily eat it, it is not dangerous to human health, and it is not invasive. Field research conducted in Serbia in 2015 (Stojanovic et al., 2017) also recorded the presence of one of the three giant *Heracleum* species, a newly introduced invasive species, *H. sosnowskyi* (syn. *H. pubescens*). It is believed that it was brought by water, more precisely the Danube River, during the great floods of 2012, and thus appeared at the only known locality in Pančevački rit, on the left bank of the Danube, in the Kovilovo area (Stojanovic et al., 2017).

Heracleum sosnowskyi is a biennial or perennial herbaceous plant. It has a well-developed, strong, deep, and branched root system that firmly anchors this robust plant in the soil. The root is perennial, so the plant can develop from the same root as a biennial or perennial species. This strong root provides high resistance and could also regenerate even after repeated mechanical removal of the above-ground part of the plant by mulching or mowing. The root zone that is crucial for stem development lies 10-20 cm below the soil surface, so if the plant is cut at ground level, regeneration occurs after some time. The only way to prevent regeneration is to cut the root within this zone. The stem is sturdy, hollow, ridged, up to 5 cm thick, 1-3 m tall, sparsely hairy, and marked with purple spots. The leaves are very large (they can reach 2-3 m), lobed, with short, rounded teeth at the tips; they are hairless on the upper surface and slightly hairy on the underside. The flowers are white (pinkish), grouped in large compound umbels located at the top of the stem, 30-80 cm wide (Figure 2). The plant flowers and bears fruit only once during its life cycle (a monocarpic species), meaning it can spend several years in the vegetative phase (although it usually flowers in the second year), but after producing seeds the plant dies. Flowering usually begins in June and lasts until August. The fruit is a schizocarp of ovate to oval shape. According to literature data, a single large plant can produce up to 10.000 seeds (Figure 3, <https://inspection.canada.ca/>). The seeds do not disperse far from the parent plant, only a few meters, but they are light and float on the water surface (for up to three days before sinking), so they can easily be transported over longer distances by watercourses, as well as by various human activities (on the wheels of machinery and vehicles, on footwear), on

the fur of wild and domestic animals, e.g. *H. sosnowskyi* reproduces exclusively by seed, which are dormant; dormancy is broken by cold and moist conditions during autumn and winter. Some of the seeds perish due to unfavorable conditions during winter, but most survive and remain in the surface soil layer (up to 5 cm), forming a large so-called “seed bank” (Nielsen et al., 2007; Šoštarčić, 2024). Data on seed viability varies, with some studies indicating that seeds do not persist for more than one year, while others suggest that seeds remain viable for about two years, meaning that most seeds perish after one year, but about 3% survive for two years (EPPO, 2020).



Figure 3. Seed of *Heracleum sosnowskyi*
<https://inspection.canada.ca/>



Figure 4. Skin hyperpigmentation
www.istockphoto.com

Heracleum sosnowskyi contains a high concentration of phototoxic substances, furanocoumarins (psoralen, xanthotoxin, bergapten, and isopimpinellin) in the sap of its stems and leaves, as well as in its fruits and seeds (EPPO, 2020). Under dry and warm weather conditions, the concentration of these compounds increases. If the stem is damaged and comes into direct contact with the skin, and the skin is then exposed to UVA radiation (sunny days), furanocoumarins become activated, bind to the DNA of skin cells, and cause skin inflammation, blistering, tissue damage, painful burns (often second-degree), and skin hyperpigmentation (Figure 4, www.istockphoto.com). In contact with the eyes, reactions in sensitive individuals may cause eye damage (Hoseini et al., 2019; Ušjak, 2019; Paramanova et al., 2024).

According to the International Agency for Research on Cancer (IARC), all three furanocoumarins contained in *H. sosnowskyi* are very dangerous: xanthotoxin in combination with UVA radiation is carcinogenic to humans, while bergapten in combination with UVA radiation is probably carcinogenic to humans. These effects result from the binding of photoactivated furanocoumarins to DNA, leading to various alterations of genetic material (Shtratnikova et al., 2025). They also interact with proteins, membrane lipids, and ribosomes, with psoralens being the most reactive (Hoseini et al., 2019). All individuals who stay or work in areas infested with *H. sosnowskyi* should be aware of the health risks posed by this plant. Skin injuries may occur during any activity that involves damaging, tearing, cutting, or touching the leaves, stems, or inflorescences, which leads to the release of toxic sap. All parts of the body must be covered with protective clothing; gloves with long sleeves should be worn, and protective glasses must be used when cutting

the plant to prevent sap from entering the eyes. Modern motorized equipment, such as trimmers, can disperse finely chopped plant material, making it necessary to wear additional eye protection and respiratory protection. In the event of contact with plant sap, the skin should be carefully washed with soap and water as soon as possible, and the affected area should then be kept out of sunlight for at least 48 hours. Early treatment with corticosteroid creams can reduce the severity of the reaction and relieve discomfort. In the following months, sunscreen should be applied to sensitive areas. If sap gets into the eyes, it should be rinsed with water and sunglasses should be worn. In cases of intense contact and severe reaction, medical attention must be sought.

In the 1940s, *H. sosnowskyi* began to be cultivated in northwestern Russia as an agricultural crop intended for silage production for feeding livestock. Cultivation of this species spread to Latvia, Estonia, Lithuania, Belarus, Ukraine, and the former German Democratic Republic. Although domestic animals readily consumed this plant, the practice was eventually abandoned, partly because plants with an anise-like odor affected the taste of meat and milk from animals that consumed them, and partly due to health risks to humans and livestock (which were later confirmed) (EPPO, 2009). There are reports that in some parts of northern Russia the plant is still cultivated for these purposes (Jahodová et al., 2007). Until the 1970s, *H. sosnowskyi* was a rare plant in natural ecosystems in Europe, but its spread has intensified since then. Particularly strong pressure has been observed in countries where it was cultivated, as plants that “escaped” into the wild rapidly became invasive. Today, this species is present in 12 European countries: Belarus, Bulgaria, Denmark, Estonia, Finland, Hungary, Latvia, Lithuania, Poland, Romania, Serbia, and Ukraine as well as in Russia (EPPO, 2020)

According to EU data (www.seedidguide.idseed.org), the main biological and ecological traits that make this species such a significant invasive organism can be summarized as follows:

- it germinates in early spring, before native vegetation emerges,
- low plant mortality once populations are established,
- very rapid growth of stems and leaf rosettes, allowing leaves to easily overtop local vegetation,
- a stable proportion of plants that flower and produce seeds,
- the ability of plants to delay flowering under unfavorable conditions until sufficient reserves are accumulated,
- early flowering during the growing season, enabling timely completion of seed development,
- the ability to self-pollinate, resulting in the production of fertile seeds,
- high fecundity even a single plant can initiate an invasion,
- high seed density in the soil seed bank, with some seeds surviving for at least two years,
- efficient breaking of seed dormancy due to low winter temperatures,
- exceptionally high germination rates,
- absence of natural enemies,
- very easy dispersal, both naturally and through human activities.

If suitable habitats are available, high rates of spread are possible at both local and regional levels, and data from countries where the invasion is present indicate that during the phase

of intensive invasion, the number of localities doubled approximately every 14 years (EPPO, 2020).

MATERIAL AND METODS

The objective of this study conducted in 2025 at the Kovilovo site was to determine how *H. sosnowskyi* behaved during the period from 2017 to 2025 under the influence of changes in the environment in which it grew.

In the area where the original *Heracleum* population is located, a survey of the current situation, i.e., plant presence, was carried out through ground-based inspections of the ruderal area around the canal and along its banks. Due to the inaccessibility of the terrain, additional surveying was conducted using drones (Figure 5). Through phytocenological surveys, the weed species accompanying *H. sosnowskyi* were identified.

RESULTS AND DISCUSSION

The example of *Heracleum sosnowskyi* population in Kovilovo clearly demonstrates the spread capacity of this plant. In 2015, when it first appeared, the plant was present on both banks of the Grbavica Canal at the edge of a planted poplar forest, covering a total area of about 150 m². The number of plants was relatively small, and within the same area *Heracleum* was “competing for space” with another invasive species, false indigo bush (*Amorpha fruticosa*).

Until 2021, this locality was monitored by associates of the Institute for Nature Conservation of the Republic of Serbia and the public enterprise “Srbijašume,” who successfully kept this population under control through mechanical and chemical control measures. When the forest was cut down in 2021 and monitoring ceased, the plant quickly “escaped” control and began to invade. On the cleared forest area, which was transformed into a ruderal habitat (Figure 6), open space, fertile soil, and favorable moisture conditions became available, all of which enabled its intensive spread.

The only obstacles were other invasive plants such as false indigo bush (*Amorpha fruticosa*), common milkweed (*Asclepias syriaca*), and many robust herbaceous, semi-woody, and woody native weed species, with which it competed quite successfully for space. Under such conditions, by 2025 the plant had spread over an area of several tens of hectares, with a tendency toward an even more aggressive expansion. Rapid spread was further facilitated by the neighboring canal, through which seeds were dispersed, so that plants can now be found up to 2 km from the original location.



Figure 6. Drone footage



Figure 5. Habitat of *H. sosnowskyi*

CONCLUSION

It is only a matter of time before *Heracleum sosnowskyi* invades the surrounding agricultural land. Cultivated crops are weak competitors against such strong invaders, and control technologies are insufficiently known and very complex, so major problems can be expected.

The greatest problems with *H. sosnowskyi* are experienced in the Baltic countries and Russia (Sazonov, 2024), and their experience clearly shows the species' strong invasive potential and how difficult, long-term, and costly its control is. It is considered that individual plants can be eradicated relatively quickly, but once colonies are established, a minimum of seven years is required for their eradication.

Heracleum sosnowskyi is listed on the A2 list of quarantine organisms, indicating that the species is already present in the EPPO region and obliging countries to implement phytosanitary measures for its control, i.e., to prevent its further spread.

To ensure that this process is as effective as possible, multiple stakeholders need to be involved, and the measures can be grouped as follows:

- monitoring and rapid detection of new populations and their mapping, which should be carried out by qualified professionals to avoid misidentification or confusion with similar species (research institutes, universities, professional services, etc.),
- education of the public and relevant target groups (farmers, road and river managers, anglers, hikers, etc.),
- identification of seed dispersal pathways and vulnerable habitats,
- eradication campaigns in cases where preventive measures fail,
- continuous field monitoring,
- investigation of control and eradication options within research institutes and other relevant stakeholders, as well as through cooperation and exchange of experience with other countries facing the same problem.

Competent authorities must have the capacity for rapid response, including field inspections, confirmation of species identification, assessment of the level of invasion, and selection of appropriate control methods.

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APPLICATION OF PEA PROTEIN ISOLATE IN THE PRODUCTION OF LACTOSE-FREE GOAT MILK KEFIR

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Abstract: Global food industry trends are increasingly focused on the development of innovative functional products with added value, such as lactose-free and high-protein foods that offer specific health benefits to consumers. At the same time, growing consumer awareness of the environmental impact of food production, particularly animal-based raw materials, has encouraged manufacturers to explore the replacement of animal proteins with plant-based alternatives. This study investigated the application of pea protein isolate (PPI) to increase the protein content of lactose-free goat kefir by 25 and 35%. Control samples without added PPI included kefir with lactose (K) and lactose-free kefir (K1). The lactose-free samples enriched with PPI, designated as KG1 and KG2, showed an increase in protein content from 2.8 to 3.5% and 3.8%, respectively. The samples were analyzed for titratable acidity ($^{\circ}\text{SH}$), pH, chemical composition, syneresis, texture and SDS-PAGE electrophoretic protein profile. The flow properties were determined by viscometry technique in the shear rate range 0 - 200 s^{-1} . Sensory quality was evaluated by trained panelists using a five-point scale. The addition of PPI significantly increased the viscosity of KG1 and KG2 samples compared to control samples at all shear rates investigated, suggesting that these samples would remain stable during pumping and transportation, which is especially important as goat milk is characterized by a fragile gel texture. The hysteresis area increased in the following order: K1 < K < KG1 << KG2. Lactose removal reduced the hysteresis area by approximately 25%, indicating weaker structural resistance to shear. In contrast, the addition of pea protein isolates significantly increased the hysteresis area, with a 46% increase at the lower enrichment level (KG1) and a 160% increase at the higher enrichment level (KG2) compared to the lactose-free control, confirming the strong structure-forming effect of PPI. Texture analysis supported the viscometry results, as significantly higher viscosity index and consistency values were observed in the enriched samples. Syneresis levels in K1, KG1, and KG2 were similar. These findings indicate that enrichment of lactose-free goat kefir with pea protein isolate represents a promising strategy for the development of high-protein functional products with solid structural stability, without increasing syneresis, thereby meeting current consumer demands for both nutritional benefits and sustainable protein sources.

Keywords: Goat milk, Kefir, Pea protein, Sustainable protein source, Texture

INTRODUCTION

Current trends in the food industry globally are focused on finding solutions to alleviate its negative environmental impact, and to provide sufficient quality foods for the growing population worldwide. To achieve this, the intensive research on the possibility of the application of new food processing technologies and non-thermal preservation methods are

ongoing (Señorans et al., 2003). Additionally, efforts have been made in discovering new protein sources to produce fortified and functional foods, as a part of emerging food trends and transition to sustainable food development and innovative green strategies (Hassoun et al., 2024).

Aligning with this, plant proteins are increasingly being used in innovative food products, to partly replace animal-based proteins, or to produce plant-based food analogues. Plant proteins are advantageous compared to animal proteins because their production has a lower environmental footprint, requiring less water and land, and results in reduced CO₂ emissions (Hertzler et al., 2020). Additionally, they are generally more cost-effective and widely available. The main plant protein sources are cereals, legumes, nuts and oilseeds. As previously reported, their protein content varies greatly and ranges from 6 to 45% (Tan et al., 2023). Plant proteins are characterized by favorable techno-functional properties in food processing, such as gelation, emulsification, and foaming, which enables their wide application in the food industry.

Consumers often connect plant-based diets with certain health benefits, which were indeed demonstrated in different studies (ex. improved weight status, energy metabolism and systemic inflammation in healthy participants, obese and type-2 diabetes patients), as reported in a systematic review by (Medawar et al., 2019). The Protein Digestibility-Corrected Amino Acid Score (PDCAAS) was developed to assess protein quality by comparing its amino acid composition with that of a theoretical reference protein that meets amino acid requirements, considering digestibility as well. Most animal proteins have a PDCAAS close to 1.0, and are commonly recognized as complete protein sources, whereas many plant proteins contain limiting essential amino acids. Although legumes are often low in sulfur-containing amino acids, pea protein ranks among the higher-quality plant proteins, with a PDCAAS of at least 0.75 (Hertzler et al., 2020). This places pea protein alongside soy, canola, potato, and quinoa as one of the most nutritionally valuable plant-based protein sources.

Kefir is a traditional fermented milk product, with an increase in production due to its specific taste and health benefits. It is obtained by sour-lactic and mild alcoholic fermentation, using lactic acid bacteria and yeasts. It is characterized by a wealth of nutrients, a diverse microbiota, natural antioxidant activity and a lower content of lactose (milk sugar) compared to yogurt (Gul et al., 2018). Kefir thus represents an ideal product for innovation and for exploring new functional formulations consistent with sustainable production principles. Among fermented dairy products, kefir is particularly recognized as a functional food and has shown substantial growth in production and consumption in recent years.

In recent years, growing attention is being directed toward lactose intolerance, as a widely present health concern. Epidemiological studies indicate that approximately 70% of the global population is affected by lactose malabsorption, with prevalence reaching as high as 95-100% in some Asian and African countries (Li et al., 2023), underlining the importance of lactose-free dairy products.

The aim of this study was to evaluate the possibility of pea protein isolate application in lactose-free goat milk kefir as a sustainable alternative to traditionally used milk proteins.

By enriching kefir with plant-based protein, the goal was to develop a product with increased protein content - aligned with current trends in the dairy industry - while simultaneously reducing its environmental footprint.

MATERIALS AND METHODS

Kefir Production

UHT goat milk (Z'bregov, Vindija) containing 2.8% milk fat and 2.8% protein was purchased from a local supermarket. To enrich the kefir, pea protein isolate with a protein content of 80.7% (Pisane™ LS, Belgium) was employed. As the starter culture, a DVS freeze-dried 'eXact Kefir1' culture (Chr. Hansen, Germany), containing the strains *Debaryomyces hansenii*, *Lactococcus lactis* subsp. *cremoris*, *Lactococcus lactis* subsp. *lactis* biovar *diacetylactis*, *Lactococcus lactis* subsp. *lactis*, *Leuconostoc* sp., and *Streptococcus thermophilus*, was used. The lactase enzyme (NolaFit 5500, Chr. Hansen / Novonesis) was applied to hydrolyze lactose.

Based on the known chemical composition of goat milk and pea protein isolate (PPI), the required amounts of each component were calculated to achieve a 25 and 35% increase in total milk protein content, resulting in fortified kefir samples containing 3.5 and 3.8% total protein. Four sample variants were produced: (1) lactose-containing control (K), (2) lactose-free control (K1), (3) lactose-free kefir fortified with 25% additional protein (KG1), and (4) lactose-free kefir fortified with 35% additional protein (KG2). The production process included the following steps: weighing milk and PPI; warm hydration of the PPI in milk using a Thermomix (Vorwerk, Germany) at 40°C for 1 h with continuous mixing (speed 3.5); pasteurization at 90 °C for 5 min; rapid cooling to 25°C; addition of lactase enzyme (1 mL/L) to the samples intended for lactose hydrolysis; simultaneous inoculation with starter culture (0.2 g/L); fermentation at 25°C for 18-19 h until pH 4.6 was reached; mixing, filling into PET bottles and final cooling (4-8 °C). Kefirs were produced two times.

PH and Titratable Acidity of Produced Kefir Samples

One day after production, pH of kefir samples was measured using digital pH-meter (Consort, Belgium). Titratable acidity was determined by titration with 0.1 M NaOH using phenolphthalein as an indicator until the titration endpoint was reached. The results were then calculated and expressed in Soxhlet-Henkel degrees (°SH).

Texture Analysis

The textural properties of kefir were analyzed one day after production using a TA. XT Plus Texture Analyzer (Stable Micro Systems Ltd., UK) equipped with a 5 kg load cell. A single compression test was applied using a back extrusion probe (A/BE; diameter 35 mm; distance 30 mm; speed 0.001 m/s) at 8°C. The data obtained were analyzed using EXPONENT software (Stable Micro Systems Ltd., UK), from which texture parameters were calculated: firmness (g), consistency (gs), cohesiveness (g), and viscosity index (gs). These parameters describe the mechanical properties of kefir.

Rheological Analysis

The rheological properties of kefir were analyzed one day after production using a Kinexus Pro+ rheometer (Malvern, UK) with a vane geometry at 8°C. To examine the viscosity and flow behavior under different shear conditions, a shear rate ramp-up and ramp-down test was performed over the range of 0-200 s⁻¹, with continuous monitoring of shear stress. Similar to yogurt and other fermented dairy products, kefir exhibits thixotropic behavior, manifested as hysteresis, the area enclosed between the ascending and descending flow curves. The magnitude of hysteresis reflects the structural stability and strength of intermolecular interactions. Hysteresis was calculated as the difference between the areas under the ascending and descending curves using Microsoft Excel. Viscosity values in the shear rate range of 10-100 s⁻¹ represent the viscosity perceived during consumption, whereas changes in the range of 100-200 s⁻¹ indicate the product's behavior and stability under processing conditions, such as transport through pipes and filling (Hovjecki et al., 2025).

Syneresis Analysis

Syneresis, the separation of whey from the protein matrix, is an undesirable phenomenon in fermented dairy products. The tendency of kefir to undergo syneresis was assessed one day after production using centrifugation method (Eppendorf 5430, Eppendorf AG, Hamburg, Germany) at 3000 × g for 10 min. The degree of syneresis was calculated as the ratio of the mass of separated whey to the initial sample mass multiplied by 100 (Setyawardani et al., 2020; Wang et al., 2019).

SDS PAG Electrophoresis

For SDS-PAGE analysis, kefir samples were taken one day after production. All samples were immediately prepared for SDS-PAGE under reducing and non-reducing conditions by mixing with the appropriate buffer solutions as previously described (Hovjecki et al., 2021, 2023) and electrophoresis was performed following the method of Laemli (1970). A standard covering a range of molecular masses (from 10 to 240 kDa) was used as the molecular mass reference.

Sensory Analysis

Kefir quality was evaluated after production by a sensory panel of seven members experienced in assessing goat milk products quality. Sensory attributes, such as overall appearance, color, consistency, odor, and flavor, were scored on a five-point scale (0-5), with half-point increments allowed (Hovjecki et al., 2025).

Statistical Analysis

One-way ANOVA was used to assess the effect of PPI addition on the examined variables. Mean comparisons were performed using Tukey's or Games-Howell post hoc test at $\alpha = 0.05$, depending on the homogeneity of variances. Homogeneity of variances was checked with Levene's test. Statistical analysis was conducted in Jamovi version 2.3.28 (The jamovi project, 2024).

RESULTS AND DISCUSSION

PH and Titratable Acidity of Kefir Samples

One day after production, pH values of samples were similar: for K, K1, KG1 and KG2 values 4.50, 4.50, 4.52 and 4.49, respectively. The addition of PPI affected buffering capacity of fortified samples, thus maintaining the similar pH values to that of control samples. However, titration with 0.1 M NaOH revealed that the lactose-free control (K1) had significantly higher acidity (52.33 ± 1.55 °SH) compared to all other samples. This discrepancy reflects the different buffering capacities of the samples. The addition of pea protein isolate in KG1 and KG2 increased protein-induced buffering capacity, reducing the titration response to the acids formed. In agreement with this, Silva et al. (2024) reported no difference in titratable acidity nor pH among control yogurt and yogurts with added pea proteins. In contrast, K1, which contains no added protein, shows weaker buffering and therefore a higher °SH value despite a comparable pH.

Texture Properties of Kefir Samples

As shown in Table 1, the addition of PPI significantly improved all analyzed texture parameters. Furthermore, consistency, cohesiveness and the index of viscosity increased depending on the PPI level. Mixed starter cultures, composed of multiple strains, such as kefir starter, can act on various hydrolysis sites of legume proteins, producing a broader spectrum of polypeptides during fermentation. Such proteolytic activity may enhance the functional and gelling properties of legume proteins, contributing to improved yogurt texture. In that regard, it was published that fermentation by kefir starter culture degrades legume proteins and improves their viscoelasticity (Li et al., 2025). On the other hand, the increased protein content results in a denser and firmer structure of the fermented dairy products (Ünal and Akalin, 2013).

Table 1. Textural properties of kefir samples produced without PPI (K-traditional kefir and K1-lactose free kefir) and with the addition of PPI (KG1- protein increase of 25% and KG2- protein increase of 35%, both lactose-free)

Sample type	Firmness (g)	Consistency (gs)	Cohesiveness (g)	Index of Viscosity(gs)
K	16.38±0.74 ^a	410.38±4.86 ^a	14.61±0.91 ^a	1.42±0.11 ^a
K1	16.40±1.18 ^a	409.32±4.81 ^a	13.49±0.65 ^a	1.20±0.01 ^a
KG1	17.60±0.65 ^{ab}	463.61±9.10 ^b	15.77±0.71 ^b	7.37±1.31 ^b
KG2	18.84±0.41 ^b	505.81±12.60 ^c	16.65±0.30 ^b	12.04±1.52 ^c

Different lowercase letters (^a, ^b, ^c) indicate significant differences between the kefir samples, $p < 0.05$

Rheological Properties of Kefir Samples

Figure 1 shows a decrease in viscosity with increasing shear rate for all samples, confirming the shear-thinning behavior of kefir. Fortified kefir samples (KG1 and KG2) exhibited significantly higher viscosity than the control samples over the entire range of shear rates investigated, indicating greater stability of these samples under mechanical stresses during processing and transportation (Table 2, Figure 1). Additionally, both KG1 and KG2 had higher hysteresis, suggesting a stronger protein matrix due to higher number of bonds. An

increase in relative protein concentration has been reported as the main cause of the higher structuring rate and complex modulus values (a measure of gel firmness) observed in pea protein-based gels (Klost and Drusch, 2019).

Table 2. Apparent viscosity (η) recorded at specific shear rates and hysteresis areas ($A_{up}-A_{down}$) of kefir samples

Sample type	η_{10} (Pa·s)	η_{50} (Pa·s)	η_{100} (Pa·s)	η_{200} (Pa·s)	$A_{up}-A_{down}$ (Pa/s)
K	0.044±0.003 ^a	0.024±0.001 ^a	0.021±0.000 ^a	0.018±0.000 ^{ab}	115.59±7.03 ^a
K1	0.04±0.000 ^a	0.022±0.000 ^a	0.018±0.000 ^a	0.016±0.000 ^a	86.93±2.18 ^b
KG1	0.104±0.004 ^b	0.038±0.001 ^b	0.029±0.001 ^b	0.022±0.000 ^b	126.8±3.22 ^c
KG2	0.140±0.004 ^c	0.052±0.001 ^c	0.039±0.000 ^c	0.028±0.000 ^c	226.24±5.11 ^d

Different lowercase letters (^a, ^b, ^c) indicate significant differences between the kefir samples, $p < 0.05$

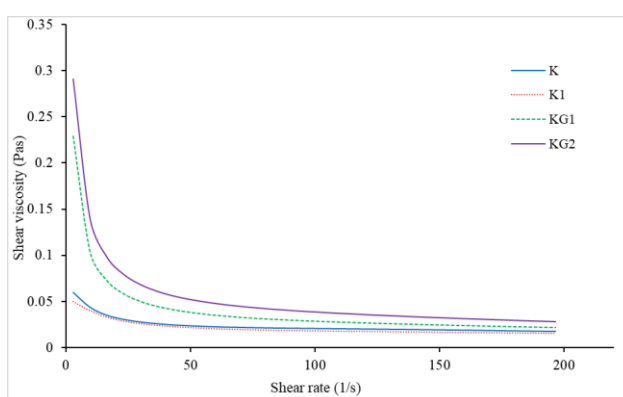


Figure 1. Change in apparent viscosity of kefir samples as a function of increasing shear rate (range 0-200 s^{-1})

Syneresis of Kefir Samples

The addition of PPI significantly increased centrifugally induced syneresis in sample KG1 compared with the control samples; however, a higher level of PPI (sample KG2) alleviated this effect, resulting in syneresis values comparable to those of lactose free-control, K. Generally, an increase in milk nonfat solids in fermented dairy products, achieved by the addition of milk or whey protein powders, is used to reduce syneresis. However, the addition of PPI resulted in a different type of protein matrix; thus, pea protein may have disrupted the integrity of the milk protein network, leading to increased syneresis. In accordance with these findings, it has been reported that a 50% replacement of milk proteins with pea proteins in hybrid yogurt caused higher syneresis compared with the control (Silva et al., 2024). Considering that a higher amount of PPI tended to reduce syneresis, optimal amounts of PPI should be identified that do not damage the kefir protein network while still providing effective water binding, a characteristic feature of PPI.

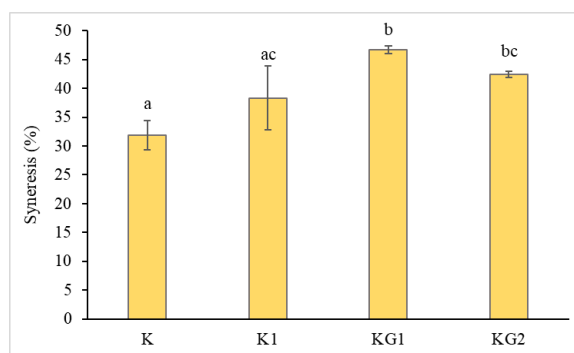


Figure 2. Centrifugally induced syneresis of kefir samples one day after production. Different lowercase letters (a, b, c) indicate significant differences between the kefir samples, $p < 0.05$

Protein Profile of Kefir Samples

Under reducing conditions, all kefir samples showed caseins (CN) as the dominant protein fractions, along with the main whey proteins (WP) β -lactoglobulin (β -LG) and α -lactalbumin (α -LA). In contrast, under non-reducing conditions, β -LG was not detected, and α -LA appeared only in trace amounts, due to heat denaturation of whey proteins and their association with casein micelles (Dalgleish et al., 1997; Guyomarc'h et al., 2003). These results indicate that the presence of pea proteins did not interfere with the formation of milk protein co-aggregates.

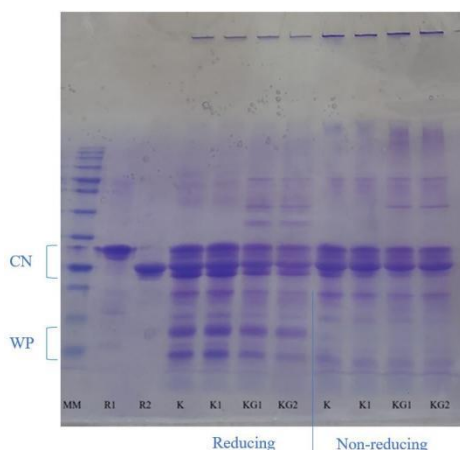


Figure 3. SDS-PAGE electrophoretogram of kefir samples in reducing and non-reducing conditions. MM - molecular weight standard; R1 - α -casein; R2 - β -casein; CN- caseins; WP- whey proteins

Heat treatment induced structural changes in pea proteins, as vicilin and legumin are known to denature in the temperature range of 75-85°C (Mession et al., 2015; Shand et al., 2007). In pea-enriched kefir samples (KG1 and KG2), a ~40 kDa pea protein fraction was observed under reducing but not non-reducing conditions, suggesting its involvement in disulfide-linked aggregates, likely corresponding to the acidic legumin (L α) subunit. Protein fractions of approximately 60 and 100 kDa were detected under both conditions, indicating non-covalent aggregation typical of vicilin and convicilin. Additionally, high-molecular-weight aggregates (>240 kDa) accumulated at the top of the gel, with greater intensity in pea-fortified samples, reflecting extensive aggregation via covalent and non-

covalent interactions. In agreement with previous studies(Akin and Ozcan, 2017; Mession et al., 2015; Silva et al., 2024), these findings suggest that pea proteins aggregate independently and do not integrate into the casein network, potentially acting as a physical barrier to casein-casein interactions.

Sensory Evaluation of Kefir Samples

Sensory evaluation showed that the addition of PPI did not negatively affect the overall quality of kefir, as all samples received high and comparable scores for appearance, colour, and odour, with no significant differences. The KG1 and KG2 samples, with 25 and 35% increased total protein content, respectively, achieved significantly higher consistency scores compared to the control samples, indicating a positive effect of PPI addition on kefir texture. Flavour scores were high and comparable among all samples, with slightly lower values in PPI-enriched formulations. This is commonly observed in beverages containing legume proteins - depending on species, there could be observed beany or bitter taste as well as sandy mouthfeel (Arbach et al., 2021).

Table 3. Results of the sensory evaluation of kefir samples, obtained using a five-point scale by an expert sensory panel (n = 7)

Sample type	Sensory evaluated properties				
	Overall appearance	Colour	Consistency	Odour	Flavor
K	4.71±0.49a	5.00±0.00a	3.71±0.57a	4.50±0.50a	4.14±0.63a
K1	4.64±0.48a	5.00±0.00a	3.93±0.67a	4.71±0.49a	3.71±0.70a
KG1	4.71±0.49a	4.86±0.38a	4.29±0.39b	4.57±0.45a	3.86±0.63a
KG2	4.64±0.48a	5.00±0.00a	4.19±0.38b	4.43±0.45a	4.07±0.45a

Different lowercase letters (^a, ^b) indicate significant differences between the kefir samples (p<0.05).

CONCLUSION

The enrichment of lactose-free goat milk kefir with pea protein isolates successfully increased the total protein content while significantly improving textural and rheological properties, particularly viscosity, consistency, and structural stability, without compromising sensory quality. The addition of PPI enhanced shear resistance and gel strength, as confirmed by viscometry, texture analysis, and hysteresis analysis. Sensory evaluation showed that PPI-enriched kefirs were rated as highly as the control samples across all parameters, with only minor flavour differences, which is typical when plant proteins are incorporated into different food matrices. Overall, pea protein isolate represents a promising sustainable ingredient for the development of high-protein, lactose-free functional kefir products with improved technological performance and acceptable sensory quality.

ACKNOWLEDGMENT

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THE EFFECT OF SELECTED WEED CONTROL MEASURES IN ANGELICA (*ANGELICA ARCHANGELICA* L.) CROP ON SOIL pH

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Abstract: A two-year field experiment evaluated the effects of different weed control measures (organic and synthetic mulches, herbicides, and controls) on soil pH in angelica (*Angelica archangelica* L.) cultivation. Most treatments did not significantly affect soil pH at the 0 - 30 cm depth. However, sawdust mulch consistently caused the greatest reduction in soil pH in both experimental seasons, indicating a pronounced acidifying effect. In addition, silver-brown polyethylene mulch foil resulted in a statistically significant pH decrease, likely due to enhanced organic matter decomposition and accumulation of organic acids. These findings highlight the importance of mulch selection, as certain materials can alter soil chemical properties and should be considered in sustainable angelica production systems.

Keywords: Soil pH, *Angelica archangelica*, Mulches, Herbicides

INTRODUCTION

Angelica (*Angelica archangelica* L.) is a biennial or perennial medicinal and aromatic plant belonging to the family *Apiaceae*, originating from Iceland and Greenland (Kišgeci, 2002; Stepanović and Radanović, 2011). It is characterized by a highly developed root system, in which the largest amount of essential oil is concentrated, making this plant primarily cultivated for that purpose (Stepanović and Radanović, 2011). It is planted in autumn from transplants, and the root is harvested in the autumn of the following year. If cultivated for seed production, exploitation lasts two years, as the flowering stem is formed in the spring of the second year (Kišgeci, 2002; Stepanović and Radanović, 2011). The essential oil is an ingredient in various cosmetic products, pharmaceuticals, strong alcoholic beverages, and others (Bhat et al., 2011), and is highly valued and in demand on the market. Plantation production of angelica faces numerous challenges, one of the most significant being effective weed control. Given the limited possibilities for herbicide application in such crops, the potential use of mulches as a non-chemical weed control measure was also investigated. In addition to their effects on weeds, mulches can have both direct and indirect effects on the crop through their influence on the soil.

These weed control methods can be useful on multiple aspects: mulching enacts a direct mechanical pressure on the ground (Ferguson et al., 2008) and prevents or postpones weed's seed germination and emergence, thus providing crops with a competitive advantage, by creating favorable conditions for their development. Meanwhile, it indirectly

regulates the soil pH and humidity, prevents temperature oscillations, and reduces pest and disease incidence (Kader et al., 2017; Xianchen et al., 2020; Pavlu et al., 2021). Also, mulch usage is recognized as an effective crop production cultivation strategy used in the face of climate change-related extreme weather conditions (increasing air temperatures, relatively little precipitation, heavy rainfalls) (Lalljee, 2013; Iriany et al., 2018). Its efficiency in weed control and effect on soil properties depends on the type of material used for mulching (organic or synthetic) and its thickness and durability within the application period (Kasirajan and Ngouajio, 2012; Lazarević et al., 2020; Dragumilo et al., 2023), so two organic (wheat straw and sawdust) and two synthetic (black agrotexile water permeable and silver-brown waterproof foil) mulches were included in this study, as well as two herbicides: metamitron and aclonifen. Bearing in mind the fact that these weed control measures may also affect the cultivated plant, this study aimed to examine their effect on soil pH, as this is one of the most important parameters that determines and influences many processes in the soil and, consequently, in the cultivated plant.

MATERIAL AND METHODS

The field trial was conducted in Kujavica village (N: 4947855; E: 404266), near the city of Šabac (Vladimirci municipality, North-West Serbia), on semi-clay soil (chemical analysis was conducted before planting, Table 1). The experiment was carried out during two consecutive years: the first experimental season (I season: November 29, 2019 - October 27, 2020), and the second experimental season (II season: November 27, 2020 - November 03, 2021). The closest weather station provided monthly means meteorological data, Sremska Mitrovica (<50 km), and it is shown in Table 2.

Table 1. Soil chemical analysis results before planting

pH		CaCO ₃ (%)	Hummus (%)	N (%)	P ₂ O ₅ (mg/100g)	K ₂ O (mg/100g)
H ₂ O	KCl					
6.20-6.35	5.10-5.50	0.00	2.24-2.45	0.15-0.17	58.00-63.10	128.00-131.00

Table 2. Meteorological data during the period of field trials

Month	Temperature (°C)		Rainfall (mm)		Relative humidity (%)	
	2019/2020	2020/2021	2019/2020	2020/2021	2019/2020	2020/2021
October	13.2	12.5	8.6	71.6	72	82
November	10.8	6.7	9.4	13.3	80	90
December	4.1	4.9	18.0	74.1	87	89
January	0.5	2.7	23.9	37.7	89	88
February	5.8	4.7	56.1	49.1	75	81
March	7.5	5.5	39.1	38.0	71	72
April	12.5	9.3	5.9	38.2	54	72
May	15.9	16.2	66.3	49.0	70	66
June	20.1	22.7	70.5	7.2	76	60
July	21.8	24.5	44.1	105.9	72	66
August	22.9	21.4	104.1	30.1	74	67
September	18.7	17.5	33.4	7.8	68	67
Oktober	12.5	10.2	71.6	71.6	82	77
November	6.7	7	13.3	163.1	90	87

A total of eight treatments were included in the two-year field experiments (2019-2021) (Picture 1): two synthetic mulches, two organic mulches, two herbicides, and two controls.

The treatments were as follows:

T1: Black, agrotextile, water-permeable mulch foil (applied layer thickness: 1 mm; specific weight: 90 g m⁻²; manufacturer: Ginegar Plastic Products Ltd., Israel),

T2: Silver - brown plastic, water-impermeable mulch film (applied layer thickness: 25 µm; manufacturer: Ginegar Plastic Products Ltd., Israel),

T3: Sawdust (mixture of black locust and oak; applied layer thickness: approximately 7-8 cm),

T4: Wheat straw (applied layer thickness: approximately 10 cm),

T5: Herbicide metamitron (product: “Metak 700 SC”, Galenika Fitofarmacija; application rate: 4 L ha⁻¹),

T6: Herbicide acetonifen (product: “Challenge 600 SC”, Bayer; application rate: 1 L ha⁻¹),

T7: Regularly hand-weeded control,

T8: Weedy (untreated) control.



Picture 1. Experimental field assay

The tested mulches were applied manually in early spring, at the onset of vegetation. Herbicides were applied foliarly, also in spring, when the weeds were at the 2-4 leaf growth stage. Application was carried out using a backpack battery-powered sprayer of the “AGM” brand, with a water volume of 300 L ha⁻¹ at a pressure of 4 bar. The positive control was regularly maintained weed-free, while the negative control was left weedy throughout the entire duration of the field experiment. At the end of the growing season, after harvesting the angelica roots, soil samples were taken from a depth of 0-30 cm to determine pH values and to identify potential differences among treatments. The analysis was conducted as follows: after drying at a temperature not exceeding 40°C, soil samples were ground in a mill to a particle size of 2 mm. Subsequently, 5 mL of the ground soil was transferred into a sample bottle, with the addition of 25 mL of KCl or distilled H₂O, depending on which pH value was being measured. Then, the suspension was mixed for 60 minutes, after which pH was measured using a previously calibrated pH-meter with buffer solutions at a temperature of 20°C ± 2°C. Once equilibrium was established, the values were read and recorded to two decimal places.

Field trials were set up according to the experimental design completely randomized block system, in three replications. All statistical analysis was performed using IBM SPSS Statistics version 25.0 for Windows. Logarithmic transformation of the raw data was used for checking the homogeneity of the analyzed groups. One-way ANOVA was applied to the data and was performed to test the effect of four mulch treatments and two controls, and their interactions. Multiple comparisons were made using Duncan's test to detect significant differences between the arithmetic means of weed biomasses and root yields ($p < 0.05$).

RESULTS AND DISCUSSION

Based on the results of soil pH measurements at the end of the growing seasons (Table 3), conducted to record potential changes compared with the values obtained before the start of the experimental seasons, it can be observed that soil pH was very similar across all tested treatments, except for treatment T3 (sawdust), where the lowest pH values were recorded in both experimental seasons (Figure 1, 2). Depending on whether the measurements were performed in KCl or H₂O, pH values in the first year ranged from 4.95 (KCl) to 5.69 (H₂O), and in the second year from 4.87 (KCl) to 5.56 (H₂O).

Table 3. Soil pH at the end of the first (A) and the second (B) experimental season

A			B		
Treatments	pH (KCl)	pH (H ₂ O)	Treatments	pH (KCl)	pH (H ₂ O)
T1	6.12	6.84	T1	5.77	6.41
T2	5.92	6.54	T2	5.86	6.53
T3	4.95	5.69	T3	4.87	5.56
T4	6.09	7.04	T4	5.91	6.8
T5	6.17	6.85	T5	6.35	6.88
T6	6.25	7.03	T6	5.87	6.45
T7	6.28	6.00	T7	6.21	6.20
T8	6.24	6.99	T8	5.82	6.25

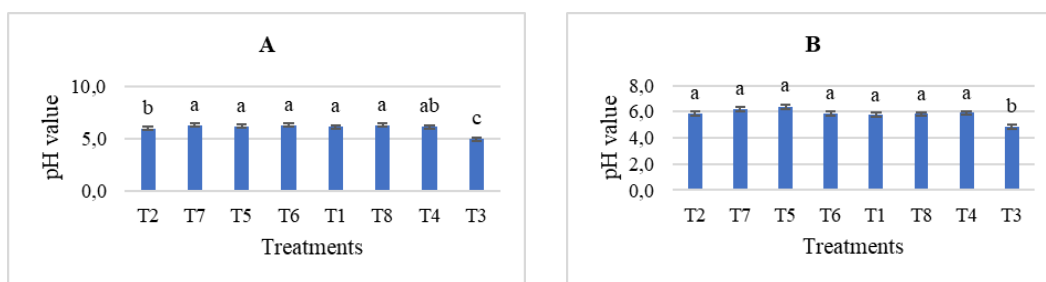


Figure 1. Soil pH reaction (KCl) in the first (A) and second (B) experimental season

At the end of the first experimental season, pH values in the other treatments ranged from 5.92 (T2) to 6.28 (T7) when measured in KCl, while the values obtained by measuring pH in H₂O ranged from 6.54 (T2) to 7.04 (T4). When the second experimental season is considered, the results are very similar to those at the end of the first season; thus, soil pH measured in KCl ranged from 5.77 (T1) to 6.35 (T5), while pH measured in H₂O ranged from 6.20 (T7) to 6.88 (T5).

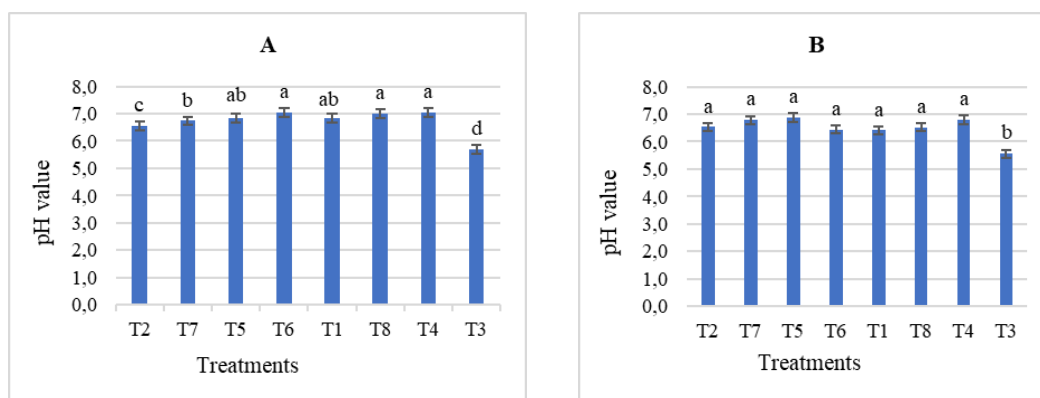


Figure 2. Soil pH reaction (H₂O) in the first (A) and second (B) experimental season

Numerous authors have reported results indicating changes in soil pH under the influence of mulches (Chan et al., 2010; Alharbi, 2015; Sharma and Bhardwaj, 2017). The results of our study show that sawdust mulch had the greatest effect on reducing soil pH at the 0 - 30 cm soil depth. The impact of sawdust on lowering soil pH is also confirmed by Mohiuddin et al. (2022), who state that sawdust, unlike lime and gypsum, decreases soil pH, and that soils amended with sawdust have a statistically significantly lower pH compared with the control. Similarly, González-Orozco et al. (2018) point out in their study on the effects of sawdust in nurseries that soil pH decreases but returns to its pre-application level very quickly.

In addition to sawdust, a statistically significant change in soil pH was also observed with the application of silver-brown polyethylene (PE) film. Sharma and Bhardwaj (2017) report that the decrease in soil pH under PE film occurs because a greater number of organic acids accumulate beneath the film as a result of faster organic matter decomposition. Wang et al. (2017) determined that after five years of consecutive PE film application, soil pH decreased by 0,4 units.

CONCLUSION

The results of the two-year field experiments indicate that the applied weed control measures did not significantly affect soil pH in most of the tested treatments. However, the organic sawdust mulch exhibited a pronounced acidifying effect, with the lowest soil pH values recorded at the 0-30 cm soil depth in both experimental seasons. In addition, the application of silver-brown polyethylene film resulted in a statistically significant decrease in soil pH, which can be associated with more intensive organic matter decomposition and the accumulation of organic acids beneath the film. The obtained results are consistent with findings reported in the literature and indicate that the choice of mulch can have an important impact on soil chemical properties, particularly soil pH, which should be taken into account when planning sustainable angelica production.

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THE PRESENCE OF HEAVY METALS IN THE WHEAT STEM AND INFLUENCE ON THE GROWTH AND HEIGHT OF THE STEM

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Abstract: One of the ways in which heavy metals get into food products is through polluted plants and animals used for their production. Thus, if plants are grown on soil with a high content of heavy metals then a part of these metals will reach in their organism. Current agricultural practices include the widespread use of chemical pesticides and mineral fertilizers known for their ability to cause negative impacts on human health and degrade the natural environment. Plants play an important role in the circulation of heavy metals in nature. Heavy metals for the most part they enter the food chain through plants. The experiment was set up in vessels where two different concentrations of heavy metal mixture 100 ppm and 250 ppm were added under controlled conditions. Higher concentrations of heavy metal mixture had negative effect on wheat stem height and plant growth was reduced. Higher concentrations of heavy metals significantly reduced plant growth in both cultivars. The aim of the research was to determine the content and influence of heavy metals on tree development in the varieties Pobeda and Ljiljana. The vegetation trial was set up in three repetitions, with a total of 36 pots in which two varieties of wheat, Pobeda and Ljiljana, were sown. Before sowing, the vessels were filled with 2 kg of Novobalt dry extract, which was subsequently contaminated with a mixture of chemical compounds of heavy metals in the form of a solution of the following compounds, namely: zinc in the form of zinc-acetate- $\text{Zn}(\text{CH}_3\text{COO})_2 \times 2\text{H}_2\text{O}$, lead in the form of lead-acetate $\text{C}_4\text{H}_6\text{O}_4\text{Pb} \times 3\text{H}_2\text{O}$, chromium in the form of chromium-trioxide- CrO_3 , copper in the form of copper-sulfate- CuSO_4 and cadmium in the form of cadmium-nitrate- $\text{Cd}(\text{NO}_3)_2 \times 4\text{H}_2\text{O}$.

Keywords: Atomic absorption spectrophotometry, Heavy metals, Wheat stem, *Triticum sp.*, Plant war

INTRODUCTION

In soil and sediment, heavy metals exist in various forms, such as: dissolved ions (e.g., Cu^{2+} , Cd^{2+} , CrO_4^{2-} , $\text{Cr}_2\text{O}_7^{2-}$ and MnO_4^{2-}), organic complexes (e.g., Cu^{2+} , Pb^{2+} , and Hg^{2+} binding to dissolved organic matter), exchangeable ions (e.g., Cu^{2+} , Zn^{2+} , Cd^{2+} , Ni^{2+} , and Pb^{2+}) adsorbed onto soil solid particles, and those (co-) precipitated as part of soil particles (e.g., $\text{Cd}_3(\text{PO}_4)_2$, ZnS , PbCO_3 , and HgSO_4). These three forms maintain thermodynamic equilibrium in activities and mutual concentration with insoluble precipitate as the dominant species (Liu et al., 2019).

Copper is one of the essential heavy metals that is not toxic in its nature metallic form, but its salt can be toxic. They are particularly toxic sulfate salts. Copper sulfate is a crystalline

salt that has a metallic taste and a blue color. In a larger dose of 0.5 g, it acts as an irritant poison and causes intestinal and stomach problems (Ali et al., 2023).

Chromium is an important micronutrient that is involved in carbohydrate metabolism lipids and proteins. It is an important metal in the production of pigments, coatings metals, woodworking and leather tanning, and is used in metallurgy and production of refractory materials, among various other applications. The most important forms of chromium oxidation are trivalent and hexavalent chromium. Trivalent chromium is largely non-toxic, and hexavalent chromium is toxic as well as carcinogenic to living organisms. Industrial waste containing chromium is known as the main source of pollution and can have a serious impact on soil and water on human health (Shin et al., 2023).

Cadmium and lead are heavy metals that, when taken into the body in the amounts more than the maximum permitted, cause various organ damage and malignant changes. They have a negative effect on blood flow, central nervous system, cardiovascular and immune system, and the kidneys. Heavy metals are a natural part of the Earth's crust. So contamination with cadmium and lead can come from an environmental source, during packaging or food processing, but also from the packaging in which it is packed (Lalić, 2024).

Differences in stress-induced effects of elevated concentrations of toxic metals indicate different tolerances of plants to metals. Based on the results of depth variation of heavy metal concentration, it is concluded that heavy metal concentrations present in solid waste samples depend on the site conditions, as well as on the conditions prevailing at the sampling sites. Based on the average concentration, the concentration of heavy metals in the collected solid waste sample was determined in the following order: $Mn > Cu > Pb > Cd$ (Zhao et al., 2017).

Contamination alongside roads was evident through significant negative correlations between metal concentrations in soil and plants samples and distance from the road edge. Only cadmium concentrations in soil and plant samples were not associated with roadside pollution. Pollution of plants and soil alongside roads did not extend much beyond 20 meters from the road (Kanmani and Gandhimathi, 2013).

Research initiated in the 1960s has shown that soil in urban and industrial areas contains extremely high concentrations of heavy metals. Plants are most sensitive to industrial pollution, which is why they are successfully used as indicators to assess environmental pollution and establish adequate biomonitoring. The aim of this study is to determine the content of heavy metals in the leaves of Plantain (*Plantago major* L.) in the Tuzla area, as well as to assess the influence of thermal power plants and industrial facilities on surrounding areas. It was found that the content of heavy metals in Plantain leaves often did not decrease with increasing distance from the dominant anthropogenic sources of heavy metal emissions (Bektić et al., 2020).

The bioconcentration factor (FB) is the concentration of heavy metals that are present in plant biomass divided by the concentration of the corresponding weight metal in the soil on which the appropriate plants are grown (Maiti et al., 2022).

Studies have shown that it is not total concentration but the reactive fraction of heavy metals in the soil that dictates their toxicity to plants, microbes, and human beings. Exchangeable forms of heavy metals that are soluble in water are much more reactive and biologically available than precipitated species (Kim et al., 2015). However, the distribution of heavy metal species is influenced by numerous environmental factors, especially pH, redox potential, clay content, Fe/Mn oxide content, organic matter content, and the presence of other cations and anions in the solid phase (Pietrzykowski et al., 2014). To accurately assess the bioavailability of heavy metals in the soil, factors of influence must be taken into account.

MATERIALS AND METHODS

The study on the influence of heavy metal mixture concentration on the dynamics of heavy metal accumulation in wheat plants and plant growth was conducted through experiments in pots in the greenhouse of the Faculty of Agriculture in Zemun, where controlled conditions of temperature and humidity were maintained. The vegetative trial was arranged in three repetitions, with a total of 36 pots in which two varieties of wheat, *Pobeda* and *Ljiljana*, were sown. Before sowing, the pots were filled with 2 kg of dry extract of Novobalt, which was subsequently contaminated with a mixture of heavy metal chemical compounds in the form of solutions of the following compounds: zinc in the form of zinc acetate- $\text{Zn}(\text{CH}_3\text{COO})_2 \times 2\text{H}_2\text{O}$, lead in the form of lead acetate $\text{C}_4\text{H}_6\text{O}_4\text{Pb} \times 3\text{H}_2\text{O}$, chromium in the form of chromium trioxide- CrO_3 , copper in the form of copper sulfate- CuSO_4 , and cadmium in the form of cadmium nitrate- $\text{Cd}(\text{NO}_3)_2 \times 4\text{H}_2\text{O}$.

The following concentrations of solutions were applied: 0 ppm (control), 100 ppm, 250 ppm. In addition to the heavy metal content in wheat plants, the height of the plants from the soil level was first measured. Afterward, the heavy metal content in wheat plants was determined. The *Pobeda* and *Ljiljana* wheat varieties were chosen because they are predominantly grown in the southern Banat region. Twelve seeds were sown in each pot at a depth of 5 cm. Samples from the trial in pots were analyzed during the tillering and heading phases, where four plants were taken from each pot. After sampling, the roots were manually separated from the wheat stem. Subsequently, the plant mass-stems were washed with distilled water and kept for several hours in 0.1 M HCl to remove soil and mineral oxides from the surface. Then, the plant mass was ground and dried in a dryer at 80°C. A 1 g sample was taken and poured with 20 ml of 60% HNO_3 . Mild boiling was performed for 2 hours. After cooling, 3 ml of H_2O_2 was added, followed by boiling for 15 minutes. The peroxide procedure was repeated. After cooling, 2 ml of HClO_4 was added, and mild evaporation was performed until dense white fumes of perchloric acid appeared (Jones and Case, 1990). After cooling, 5 ml of 5M HCl was added, and then the samples were quantitatively transferred into normal 50 ml vessels. The vessels were filled up to the final volume with distilled water. The solution was filtered through quantitative filter paper. Readings were performed using atomic absorption spectrophotometry (Varian Specter AA 220FS instrument) in acetylene/air flame. The analysis of the data obtained was conducted using the statistical software packages STATISTICA 8 for Windows and SPSS Statistics 17.0.

RESULTS AND DISCUSSION

Plant Height

The variety *Pobeda* had a slightly lower average height (38.70 cm), while the variety *Ljiljana* had a higher average height (44.50 cm). The average height of the tree per sample for the variety *Pobeda* varied from 34.00 to 42.60, and for the variety *Ljiljana* from 35.50 to 50.00 (Table 1, 2).

Table 1. Plant Height, *Pobeda* Variety (cm)

Treatment	Zn, Pb, Cr, Cu, Cd	LSD 5%	LSD 1%
Control	42.60	7.9889	14.6647
100 ppm	39.50	11.4729	21.06
250 ppm	34.00	1.8371	3.3723
Average	38.70	-	-

Table 2. Plant Height, *Ljiljana* Variety (cm)

Treatment	Zn, Pb, Cr, Cu, Cd	LSD 5%	LSD 1%
Control	50.00	1.8371	3.3723
100 ppm	48.00	1.8371	26.7668
250 ppm	35.50	5.1143	9.3881
Average	44.50	-	-

During metal mixture contamination at a concentration of 100 ppm, the *Ljiljana* variety had a plant height of 48.00 cm, while the *Pobeda* variety had a slightly lower height of 39.50 cm. At a concentration of 250 ppm, the plant height for the *Ljiljana* variety was 35.50 cm, while for the *Pobeda* variety, it was lower at 34.00 cm.

The process of photosynthesis is most sensitive to the toxic effect of lead. Long-term exposure causes inhibition of chlorophyll biosynthesis (Ernst et al., 2000; He et al., 2014). Studies have shown that lead negatively affects photosynthesis, transpiration, and stomatal conductivity when its concentration in the soil exceeds 300 ppm (Fu and Wang, 2015). Differences in the effects caused by stress due to elevated concentrations of toxic metals indicate varying plant tolerance to metals (Zhao et al., 2017).

At the cellular level, the consequences of prolonged exposure to high metal concentrations can be membrane disintegration, ion loss, lipid peroxidation, DNA/RNA degradation and finally cell death. In order for plants to develop and grow normally, they must maintain concentrations of essential elements within optimal values- a state of homeostasis (Stojanović, 2017).

Accumulation of lead in the bodies of plants and animals occurs in areas where the air, water and soil are contaminated with this chemical element. The insecticide lead arsenate, which is applied in orchards to control insects, also contributes to soil lead contamination (Premović et al., 2024).

Under the influence of higher concentrations of lead in plants, main processes, such as germination, growth and development, photosynthetic process, water intake, mineral diet

and enzymatic activity (Agami and Mohamed, 2013; He et al., 2016; Sharma and Dubey, 2005) are inhibited.

Cadmium is considered one of the most toxic elements. Although it cannot be found in nature in free form, it is still present in nature in zinc ores, but it also comes from anthropogenic sources. It is thought to be radioactive in small amounts. All cadmium compounds are poisonous, and cadmium oxide is the most poisonous. Apart from the mentioned compound, there are other known compounds of cadmium, such as: cadmium sulphide, i.e. griconite, which is the most well-known cadmium mineral, cadmium chloride, cadmium hydroxide and cadmium telluride (Turek, 2024).

Lead is present in many vegetable and animal foods in a concentration of 0.5 to 1.0 mg/kg. Lead is predominantly present in higher concentrations in fish (up to 2.0 mg/kg), molluscs and crustaceans (up to 10 mg/kg). An increase in the content of lead is mainly detected in foods that are packed in tin packaging with a lid with solder, which contains a certain content of lead. The quality of the soldering is sometimes poor, which can lead to the disintegration of those parts of the packaging, that is, to the contamination of food with lead. In very rare cases (up to 2%), it happens that in canned food stored in a container (especially during long-term storage), up to 3 mg/kg of lead accumulates, which in this case can represent a significant danger to human health. It is known that lead slows down the cognitive and intellectual development of children, and that in adults it causes an increase in blood pressure and the appearance of cardiovascular diseases. Changes in the nervous system are manifested by headache, dizziness, increased fatigue, irritability, sleep disorders, memory disorders, disorders in muscle activity and function, increased sweating, etc. Lead introduced into the human body through contaminated food can replace calcium in bones and thus become a source of permanent poisoning (Haydarov et al., 2023).

The Content of Heavy Metals in the Stem of Wheat

The content of heavy metals in the *Pobeda* and *Ljiljana* varieties varies significantly (Table, 3, 4). According to their average content in wheat plants, the heavy metals investigated in the *Pobeda* variety can be ranked in the following order:

- zinc > cadmium > copper > lead > chromium

The lead content of the *Pobeda* variety in the wheat stem is on average 3.77 mg kg⁻¹ and varies from 2.46 mg kg⁻¹ (control) to 5.45 mg kg⁻¹ (variant with 250 ppm). The cadmium content of the *Pobeda* variety in the wheat stem is on average 6.07 mg kg⁻¹ and varies from 0.65 mg kg⁻¹ (control) to 9.12 mg kg⁻¹ (variant with 250 ppm).

According to their average content in the wheat stem of the *Ljiljana* variety, the heavy metals investigated can be arranged in the following order:

- zinc > cadmium > copper > lead > chromium

The lead content of the *Ljiljana* variety in the wheat stalk is on average 3.08 mg kg⁻¹ and varies from 2.14 mg kg⁻¹ (control) to 4.33 mg kg⁻¹ (variant with 250 ppm). The cadmium content of the *Ljiljana* variety in the wheat stem is on average 10.39 mg kg⁻¹ and varies from 0.39 mg kg⁻¹ (control) to 17.31 mg kg⁻¹ (variant with 250 ppm).

Table 3. Content of Heavy Metals in Wheat Plants, Pobeda Variety (mg kg⁻¹)

Treatment	Zn	Pb	Cr	Cu	Cd	Ftest	LSD 5%	LSD 1%
Control	19.39	2.46	1.23	4.49	0.65	38832.27**	0.1197	0.1655
100 ppm	39.46	3.40	0.99	5.26	8.45	1094.38**	0.4569	0.6318
250 ppm	49.10	5.45	1.75	5.54	9.12	49105.52**	0.2678	0.3703
Average	35.98	3.77	1.32	5.10	6.07	-	-	-

Table 4. Content of Heavy Metals in Wheat Plants, Liljana Variety (mg kg⁻¹)

Treatment	Zn	Pb	Cr	Cu	Cd	Ftest	LSD 5%	LSD 1%
Control	29.99	2.14	0.58	4.65	0.39	38832.27**	0.1197	0.1655
100 ppm	77.67	2.76	0.58	5.36	13.46	62999.44**	0.3917	0.5417
250 ppm	79.13	4.33	1.23	5.41	17.31	58501.43**	0.4087	0.5652
Average	62.26	3.08	0.80	5.14	10.39	-	-	-

CONCLUSION

The vegetative trial in pots was conducted with different concentrations of heavy metal mixtures. Increasing the concentration of metal mixtures had a negative impact on plant height. Higher concentrations of heavy metals significantly reduced plant growth in both varieties. The results of the statistical analysis (analysis of variance) show that the experimental factor - the concentration of heavy metal mixtures for soil contamination - had a very significant impact on the content of heavy metals in wheat plant parts, as evidenced by the calculated F-values.

Based on the results of the research on uptake of heavy metals, it can be recommended to grow the Pobeda variety, considering that it has a significantly lower uptake of heavy metals - Zn, Cu and Cd.

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BIOCHEMICAL ACTIVITY, SIGNIFICANCE, PROTECTION AND POSSIBILITIES OF APPLICATION OF NATURAL MATERIALS IN PHARMACY AND MEDICINE

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Abstract: Medicinal raw materials originating from nature are intensively used in pharmacy and medicine. The sources of the mentioned raw materials, which are designated as drugs in pharmacognosy, primarily include biological species, i.e., plants, animals, fungi, and microorganisms; however, raw materials of mineral origin are also used. Natural substances of biological and mineral origin differ in their biochemical activity and pharmacological effect on the human body. Accordingly, in pharmacy and medicine, the most attention is paid to medicinal plants, as well as to other biological species that are pharmacologically active. Meanwhile, medicinal raw materials of mineral origin are used to a lesser extent. Due to the presence of various biochemical substances, plants exhibit pronounced pharmacological effects on the human body. Thus, for example, numerous mechanisms of action of alkaloids have been proven, as the most pharmacologically active substances of plants. Alkaloids derived from herbal drugs act on the central and autonomic nervous systems, exhibiting anesthetic, cytostatic, cytotoxic, antiarrhythmic, antibacterial, and numerous other effects. Alkaloids are also carriers of the toxicity of herbal drugs. Flavonoid and phenolic heterosides, tannins, and other plant polyphenolic substances exhibit strong antioxidant, antimutagenic, and anticancer properties and are particularly important from the aspect of application in nutrition and prevention of cardiovascular and malignant diseases. Natural raw materials of animal origin are also used in pharmacy and medicine, such as collagen, which is obtained by partial hydrolysis of ligaments and cartilage of cattle, and is used in dermatology and cosmetology. In addition, the most important proteolytic enzymes used in dermatological and cosmetic preparations are most often of animal as well as bacterial origin. Given that minerals are necessary for the normal functioning of the body, natural mineral raw materials are also used in pharmacy and medicine. Studying and knowing the biochemical and pharmacological activity of natural raw materials contributes to the possibility of finding new drugs and their application in medicine. Considering the growing pollution of all components of the environment and endangering biodiversity, it is necessary to actively implement the protection of the very important natural raw materials. The paper discusses biochemical activity, importance, protection, and possibilities of application of natural raw materials in pharmacy and medicine.

Keywords: Raw materials, Biochemical activity, Pharmacy and medicine

INTRODUCTION

Medicinal raw materials of natural origin are widely used in pharmacy and medicine. The sources of these materials, which are called drugs in pharmacognosy, primarily include

biological species - plants, animals, fungi and microorganisms, but also raw materials of mineral origin. Despite the development of synthetic drugs, herbal drugs still occupy an important place in modern pharmacy. The increasing demand for natural medicines and therapy with fewer side effects has contributed to the increased interest in phytotherapy and herbal preparations. Natural remedies are used as auxiliary medicinal products in the treatment of chronic diseases, to strengthen the immune system, in the prevention of oxidative stress, as well as in dermatology. Herbal drugs also represent a significant basis for the research and development of new medicinal substances. Many modern active pharmaceutical substances (morphine, aspirin) originate from plant sources. In this context, research, development, and possibilities of application of phytotherapeutic preparations, standardized plant extracts, and supplements rich in biochemically and pharmacologically active substances are based on a combination of traditional knowledge and modern scientific achievements. Natural raw materials of animal, microorganism, and mineral origin are also significantly used, especially in dermatological and cosmetic preparations (Kovačević, 2004; Popović et al., 2021). In this paper, the biochemical activity, importance, protection, and possibilities of application of natural materials in pharmacy and medicine are considered.

MATERIAL AND METHODS

The paper employs data analysis methods collected from relevant studies. A systematic review of scientific literature was performed, focusing on biochemical properties, pharmacological activity, significance, and applications of natural materials in pharmacy and medicine. Scientific data published in journals, conference proceedings, and works authored by the authors (self-citations) were analyzed and processed.

RESULTS AND DISCUSSION

The use of herbal drugs, which are among the oldest foundations of health treatment and preservation, dates back to ancient civilizations. Herbal drugs are plant-based raw materials used to prepare medicinal products, typically in the form of dry, whole, chopped, or powdered plant parts. These raw materials contain biologically active compounds that have therapeutic or preventive effects on various diseases. Active components such as alkaloids, flavonoids, phenolic acids, saponins, tannins, glycosides, essential oils, and others, influence different body systems and can have analgesic, anti-inflammatory, antioxidant, antimutagenic, anticancer, antiseptic, antimicrobial, diuretic, spasmolytic, and many other properties. Herbal drugs usually come from wild or cultivated medicinal plants that are collected, dried, and processed according to good manufacturing and pharmaceutical standards. They are widely used in phytotherapy, the pharmaceutical industry, cosmetology, and dietary supplement production. The biochemical components of plants determine their pharmacological action and are vital for their therapeutic effects (Kovačević, 2004; Roy, 2017; Popović et al., 2021; Šarčević-Todosijević and Malivuk, 2019; Šarčević-Todosijević et al., 2024a; Šarčević-Todosijević et al., 2025).



Figure 1. *Taxus* sp., natural habitat, locality: the western part of Bosnia and Herzegovina (collection of authors)

The most important plant that produces alkaloids is the genus *Taxus*, whose species are intensively used in pharmacy and medicine. *Taxus* sp. in nature grows as a low tree or bush (Figure 1). All parts of the plant, especially the bark, contain a mixture of diterpene alkaloids, which are extracted. Biohemijaska aktivnost i mehanizam citostatskog dejstva zasnivaju se na vezivanju alkaloida za mikrotubule deobnog vretena, čime se sprečava njihova depolimerizacija u tubulinske dimere. Biochemical activity and the mechanism of cytostatic action are based on the binding of alkaloids to the microtubules of the mitotic spindle, which prevents their depolymerization into tubulin dimers. In addition to cytostatic, alkaloids originating from herbal drugs exhibit cytotoxic, antiarrhythmic, antibacterial, anesthetic, and numerous other effects. Also, they act on the central and autonomic nervous system (Jančić, 2004; Kovačević, 2004; Šarčević-Todosijević and Malivuk, 2019; Šarčević-Todosijević et al., 2019a; Heinrich et al., 2021).

Gao et al. (2024) analyzed the chemical composition, as well as the biochemical and pharmacological activity of species of the genus *Taxus*, which, due to their significant medicinal value, represent a central object of research in the fields of medicinal chemistry and botany. All parts of the plant are rich in phytochemical ingredients, which primarily contain paclitaxel and its derivatives, various alkaloids, and flavonoids. Analysis of different medicinal parts, including bark, fresh leaves, and seeds, has led to the identification of over 800 compounds. The leaves and branches are rich in flavonoid compounds, including kaempferol, aromadendrin, apigenin, sciadopitysin, ginkgetin, luteolin, quercetin, amentoflavone, and others. They also contain 4-hydroxy-benzaldehyde, p-hydroxybenzoic acid and pyrocatechol, as well as other phenolic compounds. The total extraction of flavonoids from leaves and branches is about 128.1 mg/g of dry weight. As products of the plant's primary metabolism, polysaccharides are present in different amounts in leaves and twigs, ranging from 1.1781 to 3.0115%, with an average content of 2.1367%. The molecular weight of these polysaccharides is about 59.2 kilodaltons (kD), with a ratio of rhamnose, arabinose, mannose, glucose, and galactose of approximately 4:6:1:1:4. The essential oil content varies, being higher in the leaves, making them the primary source for extraction. Using steam distillation and gas chromatography-mass

spectrometry (GC-MS) in the examination of the essential oils of leaves and twigs of the genus *Taxus*, 30 chemical components were identified. The authors conclude that species of the genus *Taxus* are characterized by significant and diverse pharmacological activities. In addition to cytostatic and anticancer properties, they also exhibit antibacterial, antidiabetic, anti-inflammatory, and antioxidant effects (Gao et al., 2024). In addition, Šarčević-Todosijević et al. (2019b) indicate the possibility of using this plant taxon in allelopathic relationships in plant cultivation, as a basis for biological control of pathogens and parasites, safe health plant production, and environmental protection.

Flavonoids and phenolic compounds, which are often found in the form of heterosides, represent an important group of secondary plant metabolites. Binding to sugar molecules affects their biochemical activity and pharmacological effectiveness. These substances exhibit numerous biochemical activities: antioxidant, anti-inflammatory, antimicrobial, anti-cancer, anti-allergic, and cardioprotective. Thanks to their ability to neutralize free radicals and reduce inflammatory processes, they belong to the group of natural bioactive compounds of particular importance for the prevention and treatment of chronic diseases. In pharmaceutical practice, herbal drugs with flavonoid and phenolic heterosides are used in various pharmaceutical forms: teas, tinctures, extracts, capsules, and tablets, as well as in dermal preparations. Some of the well-known representatives of herbal drugs include ginkgo leaf (*Ginkgo bilobae folium*), hawthorn leaf and flower (*Crataegi folium et flos*), *Solidaginis herba*, birch leaf (*Betulae folium*), linden flower (*Tiliae flos*), and many others, which are traditionally used as auxiliary medicinal agents (Sarić, 1983; Kovačević, 2004; Šarčević-Todosijević et al., 2024a,b; Šarčević-Todosijević et al., 2025). *Ginkgo biloba* is one of the most important plant species used in pharmacy and medicine. *Ginkgo biloba* L. (figure 2) is a deciduous tree and the only surviving representative of the once large Ginkgophyta group (Jančić, 2024). In phytotherapy, the leaf (*Ginkgo bilobae folium*) is used, most often in the form of standardized dry extracts (e.g., EGb 761), which are obtained by a controlled extraction process (Kovačević, 2004; Šarčević-Todosijević et al., 2024a).



Figure 2. *Ginkgo biloba* L., locality: Nova Pazova, Serbia (collection of authors)

Mohammadi Zonouz et al. (2024) state that chemical analyzes revealed that *Ginkgo biloba* contains hundreds of biochemically active metabolites, such as terpene-lactones, as well as bilobalide, then flavonols - quercetin, rutin, isorhamnetin, kaempferol glycosides and procyanidin B2. Due to its active compounds, *Ginkgo biloba* exhibits anti-inflammatory,

anti-apoptotic, anticancer, neuroprotective, cardioprotective, hepatoprotective, antiviral, antibacterial, pulmonoprotective, renoprotective, retinoprotective and other beneficial properties (Mohammadi Zonouz et al., 2024). The plant genus *Echinacea* is also a significant source of phenolic and flavonoid heterosides, which have antioxidant, anti-inflammatory, and immunostimulating effects. It is used in phytotherapy to strengthen the immune system and to prevent and alleviate colds and infections, as well as in the preparation of various herbal formulations (Kovačević, 2004). Manayi et al. (2015) stated that different classes of secondary plant metabolites, such as alkamides, caffeic acid derivatives, flavonoids, polysaccharides and glycoproteins are the main biologically and pharmacologically active constituents of *Echinacea* sp. Capek et al. (2015) state that numerous clinical trials have been conducted to test the efficacy of constituents isolated by different procedures from different species of the *Echinacea* genus, describe their active principles; however, the identification of all metabolites has not yet been completed. The authors further report that *E. purpurea*, *E. angustifolia*, and *E. pallida*, the three most studied *Echinacea* species, are particularly rich in pharmacologically active metabolites such as alkamides, polysaccharides, glycoproteins, phenylpropanoids, phenolic heterosides, and flavonoids, which are obtained from different plant parts, including roots, stems, leaves, and flowers. It has been demonstrated that these compounds are responsible for the observed immunostimulatory and anti-inflammatory activities. Immunomodulatory effects are mainly attributed to polysaccharides. They increase the chemotaxis of macrophages, stimulate the production of IL-10 (interleukin-10), IL-6 and IL-1- β , have an adjuvant effect on the cytokine responses of human T-cells and inhibit the growth of pathogenic fungi. The polysaccharide-phenolic complex also has an anticoagulant effect (Capek et al., 2015). Rutin, a flavonoid heteroside present in buckwheat (*Fagopyrum esculentum*), black elderberry (*Sambucus nigra*), horse chestnut (*Aesculus hippocastanum*) and many other plants, is one of the most researched natural antioxidants in the field of phytotherapy. Rutin prevents oxidative damage to lipids, proteins and DNA and contributes to the prevention of numerous chronic diseases (Kovačević, 2004; Šarčević-Todosijević et al., 2024a; Šarčević-Todosijević et al., 2025). Rahmani et al. (2022) state that the antioxidant, anti-inflammatory and anti-apoptotic properties of rutin have been scientifically proven. The authors emphasize the hepatoprotective, renoprotective and cardioprotective effects of rutin. The antioxidant effects of rutin are manifested by increasing the activity of antioxidant enzymes such as GST (glutathione-S-transferase - participates in the metabolism of glutathione, one of the most important antioxidants), GGT (γ -glutamyltransferase), CAT (catalase) and others (Rahmani et al., 2022). Ren et al. (2024) report that *Sambucus nigra* exhibits multiple biological activities, including antidiabetic, anti-infective, antineoplastic, and antioxidant effects. *Sambucus nigra* L. is a widespread deciduous shrub. The fruits are used in the food industry for the production of various types of dietary supplements (Kovačević, 2004). A commercial extract preparation, Sambucol®, has been used clinically in the treatment of viral respiratory infections. The main components responsible for the biochemical and pharmacological activities are phenolic compounds, such as simple phenolic acids, anthocyanins, and other flavonoids, as well as tannins. Ren et al. (2024) emphasize that dapagliflozin, an antidiabetic drug approved by the U.S. Food and Drug Administration (FDA), was developed from the hydrolysable tannin β -pentagalloylglucose, a secondary metabolite found in *Sambucus* species and other plants.

Due to their pronounced biochemical activity, herbal drugs play a significant role in the treatment and alleviation of respiratory disease symptoms. Plants used in the therapy of respiratory diseases exhibit various pharmacological effects, which include anti-inflammatory, antimicrobial, expectorant, and bronchodilator effects. Herbal drugs such as eucalyptus, thyme and liquorice have been proven to be effective in the treatment of various symptoms of respiratory diseases (Kovačević, 2004; Šarčević-Todosijević et al., 2019a). In addition, phytotherapy may help reduce side effects associated with the long-term use of pharmaceutical drugs. Many synthetic drugs, especially those that act as bronchodilators, can have side effects such as tachycardia, insomnia, or headache. Plants such as *Ephedra sinica* achieve a similar bronchodilator effect, without the side effects (Dousari et al., 2022). *Plantago lanceolata* L., a plant from the Plantaginaceae family, is often used in pharmacy and medicine as an expectorant, as well as to relieve inflammation of the mucous membrane of the mouth and throat. It exhibits antimicrobial, spasmolytic, and astringent activities. It is used externally for the treatment of injuries and wounds. *Plantago* sp. is a perennial herbaceous plant. It grows along roadsides, in settlements, and on meadows and clearings. The herbal drug is derived from dried leaves (*Plantaginis lanceolatae folium*). It is dried in a thin layer at 44-50°C. The leaf is slimy and bitter in taste, odorless. The leaf contains monoterpene iridoid heterosides. The most important are aucubin (2.5%) and catalpol. The drug is also rich in polyphenols, phenolic acid heterosides, coumarin (esculetin), flavonoids and tannins. It also contains saponins, mucilage, and silicic acid salts (Jančić, 2004; Kovačević, 2004; Petrović et al., 2022). Adom (2017) points out that antitussive, anti-inflammatory and antimicrobial effects are the key effects of *Plantago* sp. in the therapy of diseases of the respiratory system. Polysaccharides and iridoid glycosides, especially aucubin, are responsible for the anti-inflammatory effect on the mucous membrane of the respiratory tract. Flavonoids, such as luteolin and apigenin, act as antioxidants and mild bronchodilators, which can relieve asthma symptoms. The results of the study indicate that extracts of *Plantago* sp. exhibit antimicrobial activity against bacteria that cause respiratory tract infections, such as *Streptococcus pneumoniae* and *Haemophilus influenzae*. Animal studies and human observations have shown that syrups and extracts of *Plantago* species can reduce coughing and improve breathing in cases of acute bronchitis (Adom, 2017).

Although plants are used significantly more in pharmacy and medicine, materials of animal origin are also used in these fields. Animal drugs can be isolated from the animal organism by simple procedures. Fish oil, lard, beef tallow, lanolin, gelatin, and ambergris are most often used in pharmacy and medicine. Ambergris is a pathological, hardened mass obtained from the intestinal tract of the biological species *Physeter catodon*, *Physeteridae*. Ambergris has long been used in cosmetology and perfumery because of its pleasant aroma and its fragrance-fixing properties. The main ingredients are coprosterol, coprostanone, and triterpene alcohol ambrein (25%). The largest quantities of ambergris are obtained from killed animals. The collection of ambergris is regulated by the "*Marine Mammal Protection Act*", and its trade is illegal today. Proteolytic and amylolytic enzymes of plant, animal, and microorganism origin are intensively used in cosmetic preparations, as well as for therapeutic purposes. Bromelain is a complex of proteolytic enzymes from the fruit of *Ananas comosus* (*Bromeliaceae*) and is used as an anti-inflammatory and anti-edematous agent. Protein complexes from plants and marine organisms are increasingly used in dermatology and cosmetology. They are important due to diseases affecting livestock, whose tissues (such as ligaments and cartilage) are used to obtain collagen. Collagen is a

polypeptide that makes up about 70% of connective tissue, as well as skin, bone and tooth tissue. In dermal preparations, it forms a protective film, enables hydration of dry skin and contributes to its elasticity. It is obtained by partial hydrolysis of the ligaments and cartilage of cattle. The results of conducted scientific research suggest that hydrolyzed collagen (HC) supplementation may have a positive effect on skin health. However, further large-scale randomized controlled trials are needed to confirm these findings (Kovačević, 2004; Popović et al., 2021; Pu et al., 2023).



Figure 3. *Ovis* sp. and ecosystems of xerophilous meadows and pastures, locality: Manjača, Bosnia and Herzegovina (collection of authors)

Bee products are intensively used in nutrition, dietetics, pharmacy, medicine, and cosmetology. Bee products are: honey, royal jelly, pollen, bee venom, beeswax, and propolis. There is great interest in the use of bee products in medical practice, and a new branch of medicine, apitherapy, has even been established. The importance of bees is not limited to their products, which are valuable both nutritionally and medicinally. Bees are responsible for 87.5% of the pollination of plants of the Magnoliophyta division, which is especially important in agricultural production. Due to the intensification of agricultural production, climate change and environmental pollution, it is necessary to develop sustainable strategies that will ensure safe food production. In this sense, the importance of bees in the pollination of Magnoliophyta, and consequently in achieving higher yields of fruits and seeds, especially of cultivated plants, is increasing. Without bees, there would be a decrease in the number of Magnoliophyta and a disruption of the ecological balance in the entire biosphere (Oljača, 2008; Šarčević-Todosijević et al., 2023a,b,c). In addition, Popović et al. (2023) report that the world economy is reduced by 212 billion dollars due to the mass death of bees, and 30% of bee colonies in the USA and about 20% in EU countries have already been destroyed. Bee losses due to pesticide poisoning are rising each year. Most pesticides registered for agricultural use do not pose significant risks to bees, but only when populations are exposed to individual compounds. However, their combination, especially insecticides and acaricides with fungicides, is more toxic to bees than the individual compounds. Insecticides weaken bees' resistance and promote the development of diseases, such as increased susceptibility to the parasitic species *Nosema ceranae*. The risk of pesticides to bees can be reduced by applying insecticides in the evening, when bees are inactive. It has even been suggested to place beehives on house rooftops as a measure to help prevent the decline of bee populations (Popović et al., 2023).

Mineral substances are essential for the structure and proper functioning of the body, which is why natural mineral raw materials are widely used in pharmacy and medicine. Numerous plant species, such as birch, nettle, yarrow, beans and seaweed, are important sources of these substances and are used to treat conditions resulting from their deficiency in the body.

In pharmacy and medicine, plants are used most frequently, although other biological species are also utilized, while medicinal raw materials of mineral origin are used to a lesser extent. Natural inorganic raw materials used in pharmacy and cosmetology are chalk, diatomaceous earth, clay, kaolin, and talc. Clay is a colloidal substance of sedimentary origin. Pure clay, or combined with plant materials and plant extracts, is used in cosmetic masks. Sterilized kaolin can be used as an adsorbent in the treatment of gastrointestinal diseases. More commonly, it is used in dermatology in the form of a powder or paste. Talc is a white, soft mineral powder, composed of magnesium silicate with water. It is used in cosmetics as a protective and absorbent agent; it is the basis of powder (Kovačević, 2004; Kovačević, 2009; Popović et al., 2021; Šarčević-Todosijević et al., 2022).

Intensive environmental pollution, climate change, and the rise in global average temperatures represent a serious threat to biodiversity and ecosystems, which are the only sources of food, oxygen, but also materials necessary for the progress of pharmacy, medicine, and other areas of human activity. Preserved biodiversity, especially plant diversity, helps mitigate climate change by absorbing carbon dioxide from the atmosphere. That is why the protection of biodiversity is one of the key conditions for preserving the stability of the planet and ensuring a sustainable future for humanity (Šarčević-Todosijević et al., 2023c; Šarčević-Todosijević et al., 2024b).

CONCLUSION

Biodiversity provides key natural resources and materials for the technological progress of various industries, with plants having particularly great economic and health importance. Thanks to their biochemical and pharmacological activity, plant taxa and their metabolites, as well as natural substances of animal and mineral origin, are widely used not only in medicine and pharmacy, but also in agriculture and environmental protection. That is why the protection of plant and animal species, as well as abiotic components of the ecosystem, is a priority for the survival and further progress of humanity.

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INTEGRATING UV-VIS SPECTROPHOTOMETRY INTO FOOD QUALITY MANAGEMENT SYSTEM

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Abstract: UV-Vis spectrophotometry has become a common and very practical tool in food quality control because it is quick, simple to use, and sensitive enough for everyday analyses. With this technique, laboratories can easily check the levels of nutrients, colorants, additives, and natural pigments in different food products. It is also frequently used to screen for possible contaminants, detect signs of adulteration, and observe how products change during processing or storage. In the context of quality management, UV-Vis helps laboratories make informed decisions and stay aligned with standards such as HACCP, ISO 22000, and ISO/IEC 17025. These systems depend heavily on reliable analytical results to identify potential hazards, confirm critical control points, and keep product specifications stable over time. Although its selectivity is lower than that of more advanced chromatographic methods like HPLC or GC, UV-Vis remains widely used because it is affordable, fast, and requires minimal preparation. This review summarizes the fundamental principles of UV-Vis spectrophotometry, discusses its key applications across different food categories, and illustrates how the method contributes to quality management and food safety in modern production. The paper also emphasizes its broad role in ensuring product safety and its ongoing relevance as part of integrated quality management systems.

Keywords: UV-Vis spectrophotometry, Food, Quality, Control, Analysis, Safety, Analytical methods, Monitoring

INTRODUCTION

Safety of the food is vital to food businesses and protects consumers from possible health-related threats. Quality of food is the basis of several concepts including the organoleptic qualities of food (smell, taste, sight) and their nutritional value. In addition to quality of food, food safety provides producers with information necessary to reduce the risk of contamination of their products by potentially dangerous microorganisms (and/or other hazards) via the use of food safety procedures. Ultraviolet-visible spectrophotometry has become an essential analytical technique for quality control and management in the food industry (Rocío Ríos-Reina, 2023). Ultraviolet-visible spectrophotometry is one of the many analytical techniques available for the measurement of the absorption (or transmission) of light within a specific wavelength (range between 200 nm to 700 nm) by a sample and is primarily used to determine the qualitative and quantitative analysis of the chemical components present in a sample. Using Beer-Lambert Law, this analytical technique measures the amount of light absorbed by the chemical components that are responsible for the qualitative and quantitative identification of the chemical components

(nutrients, colorants, additives, contaminants etc.) present in the sample. The amount of light absorbed is directly proportional to the number of chemical component(s) that cause the light to be absorbed by the sample.

$$A = \epsilon \cdot c \cdot l$$

A = absorbance

ϵ = molar absorptivity coefficient ($\text{L} \cdot \text{mol}^{-1} \cdot \text{cm}^{-1}$)

c = concentration of the analyte ($\text{mol} \cdot \text{L}^{-1}$)

l = path length of the cuvette (cm)

As a result of its simplicity, rapidity, low cost, and nondestructive nature, ultraviolet-visible spectrophotometry has been widely applied in both qualitative and quantitative analyses in the food industry. For example, ultraviolet-visible spectrophotometry has been used to detect adulterations (e.g. dilutions or contaminants), quantify additive levels (preservatives, dyes), and monitor changes resulting from processing.

This review highlights the principles behind ultraviolet-visible spectrophotometry and emphasizes its qualitative (presence/absence and fingerprinting) and quantitative applications in different areas of the food industry, using examples of recent studies and current practices in the food industry.

A UV-Vis spectrophotometer uses a light source that includes a deuterium lamp for the ultraviolet spectrum and a tungsten lamp for the visible spectrum, and the monochromator selects a wavelength for which to allow the selected wavelength of radiation to pass through the sample. As a result of this requirement, the sample must be clear or transparent, thereby requiring extraction or dilution before analysis if the sample is solid or contains suspended particles. Calibration curves established from known concentrations of standards must be prepared prior to quantitative analysis.

In addition to ensuring food safety and quality, the implementation of ISO 9001, HACCP, and other quality standards in laboratory practice - especially in UV-Vis spectrophotometry - represents a fundamental aspect for regulatory compliance in the food industry. These standards define the functions of laboratories, provide guidelines for validating analytical methods, and describe the presentation of analytical data that will support decision-making in the food industry.

Application of UV-Vis Spectrophotometry in Quality Control

Dairy Products

For instance, using UV-Vis spectrophotometry, Xie et al. (2015) proposed the development of a rapid and sensitive colorimetric method called UV quantification for the detection of melamine (MEL) in milk samples. This method was based on the aggregation of gold nanoparticles (AuNPs) induced by the interaction of AuNPs with MEL, causing the AuNPs to change from red to purple. Results indicated that the amount of MEL present in milk samples could be determined in approximately 15 min, with a minimum limit of detection of 2 ppm (Xie et al., 2015).

With respect to hazardous substances, the UV-Vis spectrophotometer plays an additional role in investigating the stability of nutrients in milk (Mohamed and Farag, 2022). It assesses the interactions between milk proteins and some lipophilic nutrients such as lutein using UV studies at 500 nm, in terms of changes in turbidity. Since the aromatic amino acids contained in milk proteins absorb light at 280 nm, the amount of protein in milk can be easily measured.

Beverages (Alcoholic and Non-Alcoholic)

The use of UV-Vis spectroscopy in the quality control of alcoholic and non-alcoholic beverages is widespread because of its rapidity, simplicity, and adherence to industry standards. The UV-Vis technique has standard procedures for determining many important features of beverages. Beer brewing is one of the most well-known uses of UV-Vis, in particular for determining the color and bitterness of beer. Isooctane extracts hop-derived iso- α -acids, and the amount of these compounds present in isooctane is determined by measuring the absorbance at approximately 275 nm (the International Bitterness Unit (IBU)). It allows the brewer to determine the exact amount of substances that contribute to the bitter taste of the beer (Do Nascimento et al., 2021).

In winemaking, UV-Vis is also critical for tracking the color and phenolic content of wines (Onache et al., 2023). The absorption of total phenols occurs about 280 nm, whereas the absorption of anthocyanin, which contributes to the color of red wine, occurs in the visible spectrum at wavelengths of 520-540 nm. Therefore, UV-Vis enables rapid determination of the polyphenol content and color strength of wine. Some researchers have even used multivariate statistical analysis (i.e. PCA) in combination with complete UV spectra (200-600 nm) to identify grape varieties and vintages based on the specific phenolic fingerprint of each.

Fruit juice clarity and haze are other important quality parameters that affect the visual appearance and acceptance of fruit juices (Pappalardo, 2022). Caffeine absorbs strongly at about 273 nm; therefore UV-Vis is often used to measure caffeine in non-alcoholic beverages, i.e., coffee and tea. Colorimetric techniques using UV-based methodology are also commonly used to perform routine color monitoring to ensure product consistency.

Modern breweries mainly rely on UV-Vis sensors to rapidly and effectively monitor a variety of quality indicators such as color, bitterness, carbohydrate content, polyphenol content, and even sulfite concentration. All things being equal, UV-Vis is a key analytical instrument for ensuring the quality of beverages as it provides rapid, reagent-free assays that often meet or exceed regulatory requirements.

Vegetable Oils and Fats

UV-Vis spectroscopy is a valuable method for evaluating the quality of edible vegetable oils and for detecting adulterations. Vegetable oils such as olives and sunflowers contain natural UV-absorbing compounds such as chlorophyll and carotenoids. Additionally, when oils undergo degradation - especially oxidation - conjugated compounds are formed that also absorb UV light. For example, conjugated diene formation, indicative of early oxidation products, results in absorbance at approximately 232 nm, whereas conjugated

triene formation, indicative of later stage oxidation, results in absorbance at approximately 270 nm, and thus UV-Vis spectroscopy can be used to evaluate rancidity.

A study demonstrated how UV-Vis, in combination with multivariate analysis (MCR-ALS), can follow the decrease of α -tocopherol (vitamin E) in oils as they are heated (Gonçalves et al., 2014). As the level of antioxidants decreases, the level of UV-absorbing oxidation products increases, demonstrating that UV-Vis can evaluate both the degradation of oils and the nutrient loss during frying process.

UV-Vis is also utilized to measure the levels of pigments in oils. Chlorophyll absorbs strongly at a wavelength of 670 nm, whereas carotenoids absorb at wavelengths of 450-480 nm. By measuring the absorbance at these wavelengths, the degree of freshness and type of oil can be assessed. UV-Vis assays have been used to measure total chlorophyll and carotenoids in olive oils, resulting in distinct differences in the fresh and extra-fresh grades (Borello and Domenici, 2019).

Another significant application of UV-Vis is the detection of adulteration. When UV-Vis spectra collected between 200-700 nm are analyzed using chemometric techniques, they can differentiate between pure olive oil and mixtures containing lower-cost seed oils such as sunflower, corn, or canola. Research shows that even portable UV-Vis instruments can detect adulteration levels of 10% or higher due to variations in the patterns of oxidation of fatty acids and in the pigment content. More sophisticated techniques, such as photoionization IMS (PIIMS), have further decreased detection limits, allowing for the identification of olive oil adulteration at levels comparable to 10%, within a time frame of less than 20 minutes (Garrido-Delgado et al., 2018).

In conclusion, UV-Vis spectroscopy offers a fast, environmentally friendly means for screening oils for oxidative stability, freshness and purity. However, for detecting very low levels of adulteration (less than 5%), more sensitive analytical techniques will likely be required.

Grains and Cereals

UV-VIS Spectroscopy has very low frequency of application in Grain/Cereal analysis, yet it is an important tool for that type of food. Examples include measurement of specific pigments and some of the nutrients found in Grains (Yisak, 2022); the antioxidant properties, including polyphenols; and the mineral properties of flours (Jaćimović et al., 2023) that exhibit absorption in the ultraviolet spectrum and therefore may be utilized to assess flour quality. UV-VIS is also an important tool in determining protein concentrations in Flour by employing Colorimetric Assays. An example of a common assay is the Biuret Reaction (which creates a Violet colored Complex that can be measured at 540-560 nm).

UV-VIS is also a useful tool in contaminant analysis. Many toxic mycotoxins (such as Aflatoxins and Ochratoxins) display a High level of UV Absorbance; therefore, UV-VIS is a viable Rapid Screening Method and/or can be employed as a Detector in more sophisticated procedures such as HPLC.

High End Methods such as HPLC or LC-MS are considered the Gold Standard for Toxin Detection; however, UV-VIS can provide initial, rapid insights into the presence of Toxins that contain Conjugated Double Bonds.

Additionally, researchers have successfully applied Chemometric Techniques utilizing UV-VIS Spectral Data to Identify Adulteration in Milled Products such as Bread/Flour, e.g., Wheat Flour blended with lower cost Grains such as Barley.

UV-VIS performs a more defined role in Grain Analysis generally, typically supporting other established methods for Protein Level Determinations, Sugar Content Determinations, or Contaminant Testing.

Other Foods (Honey, Spices, etc.)

UV-Vis Spectrophotometry is not limited to General Food Analysis; UV-Vis is also gaining utility for Specialty Foods such as Honey and Spices. Honey is known for being a Superfood containing a wealth of Nutrients along with its High Sugar Content and Polyphenols as part of its Distinct Secondary Metabolite Bioactive Composition (Ansari et al., 2018). These make UV-VIS a rapid and efficient Tool for Honey Authentication.

For Spices and Extracts, UV-VIS can aid in Identifying and Quantifying Key Active Compounds. UV-VIS measures Curcumin in Turmeric at 425nm and Capsaicinoids in Chili Peppers near 280nm. UV-VIS can also Identify Illegal Dyed Products that have been Tampered with. Food Colorants, whether Natural or Synthetic, are commonly Analyzed with this Method. Dyed Products such as Tartrazine and Sunset Yellow absorb Strongly in the Visible Spectrum, making them Easy to Detect and Quantify. In summary, UV-VIS Spectrophotometry is a valuable Addition to Food Testing, allowing the monitoring of Color, Additives and Product Purity in everything from Honey to Spices.

UV-Vis Spectrophotometry in Food Quality Management Systems

To ensure that analytical information generated in food laboratories accurately and reliably reflects the quality of food products, UV-Vis spectrophotometry should be implemented in conjunction with quality management systems (QM). International Standards (2017, 2018) and Regulations Provide Frameworks for QM in Food Laboratories. Key to establishing a quality management system is compliance with relevant international standards and regulations that guide the establishment of laboratory quality management systems.

ISO/IEC 17025 - General Requirements for Testing and Calibration Laboratories

In addition to providing guidelines for general laboratory operations, including proficiency, objectivity and reliable performance of laboratories, ISO/IEC 17025:2017 provides specific guidance for ensuring that UV-VIS spectrophotometers have been properly calibrated, validated and maintained.

Applicability to UV-Vis Spectrophotometry:

- The standard requires that UV-Vis methods use documented Standard Operating Procedures (SOPs) and reference materials that are traceable,

- The standard requires that all UV-Vis methods undergo thorough validation and include assessments of quantitative capability (LOQ), linearity, accuracy, precision and LOD,
- By requiring that laboratories utilize QC samples regularly and participate in proficiency testing programs for UV-Vis, the standard supports the reliability of UV-Vis data and facilitates comparison among laboratories.

HACCP - Hazard Analysis and Critical Control Points

The purpose of a HACCP (www.fao.org/4/y1579e/y1579e03.htm) food safety system is to identify, evaluate and control physical, chemical and biological hazards in the food processing environment. In many cases, the use of UV-Vis spectrophotometry can be useful in the development of HACCP plans, particularly at CCPs. Ensuring that the analytical data generated from UV-Vis is properly documented and traced, may be beneficial in using UV-Vis as a CCP verification tool. Additionally, UV-Vis can assist in verifying control measures by detecting spoilage indicators or oxidation products in fats and oils.

ISO 22000 - Food Safety Management Systems

ISO 22000:2018 builds upon HACCP principles but goes further by providing the requirements for a Food Safety Management System (FSMS) and provides for certification against it. ISO 22000:2018 defines the steps organizations need to take to demonstrate their ability to manage food safety risks so that they can produce food that is safe to eat. ISO 22000:2018 also ensures that laboratory data generated during the use of UV-Vis instruments is reliable and supports informed decisions related to food safety. UV-Vis methods can be utilized to monitor chemical contaminants in foods that affect food safety including mycotoxins, food colorants, and preservatives.

Good Laboratory Practice (GLP) and Good Manufacturing Practice (GMP)

In addition to verifying that raw materials and final products meet established standards, and that labeling claims are accurate, GLP validation of UV-Vis methods ensures that these methods are both reliable and reproducible and that all aspects of the methods have been documented.

Advantages and Limitations of UV-Vis Spectrophotometry in Food Analysis

UV-Vis spectrophotometry is widely used for food quality control due to numerous advantages of this technique, including speed, affordability, and flexibility. Using a single instrument, UV-Vis spectrophotometers measure color, clarity, and concentration of samples with minimal sample preparation. This technique is non-destructive and produces results within seconds to minutes, making it ideal for continuous monitoring of food quality.

One of the major advantages of UV-Vis spectrophotometry is accessibility. Portable systems are common today and allow for on-site testing in food processing plants or in the field; this technology requires minimal consumable supplies, typically limited to solvents or simple reagents. Full-scan UV-Vis methods are particularly advantageous for developing “fingerprints” for new products and can measure multiple analytes simultaneously.

Like any analytical method, however, UV-Vis has limitations. Derivatization or other forms of treatment may be required when analyzing compounds that do not absorb radiation in the visible or ultraviolet regions of the electromagnetic spectrum, i.e., many sugars and salts. Generally, UV-Vis methods have less sensitivity and specificity than more sophisticated techniques, e.g., mass spectrometry or chromatography. Additionally, broad, overlapping absorption bands are often observed in UV-Vis spectra, which complicates identification of specific ingredients in complex food matrices. Turbidity, light scattering caused by emulsified fat, and matrix effects can all interfere with UV-Vis measurements, and careful construction of calibration curves must be performed to obtain accurate results. UV-Vis may lack the detection limits needed to detect trace levels of contaminants, or subtle adulteration in foods. While UV-Vis is an excellent tool for quality control, its lack of discriminative power compared to more advanced spectral technologies, as noted by Farag et al., precludes it from being a standalone method. Therefore, UV-Vis is often used as a screening tool, with subsequent confirmatory analysis using more sensitive methods (e.g., PCR, HPLC).

CONCLUSION

UV-Vis spectrophotometry continues to be an important and versatile tool in quality assurance (QA) programs in the food industry. Its ability to rapidly and cost-effectively assess color, concentration, and compositional fingerprints makes it a valuable tool for many types of food and beverage products, including dairy, meat, beverages, oils, grains, and specialty foods. The fundamental benefits of UV-Vis spectrophotometry make it well-suited for both routine QA and process monitoring; these include speed, ease-of-use, and low operating costs.

The inclusion of UV-Vis spectrophotometry into larger quality management frameworks, such as ISO/IEC 17025, ISO 22000, HACCP, and GMP, will provide traceable, verifiable information that supports both food safety and regulatory compliance. Specifically:

Maintaining the sensory attributes and consistency of the product,
Validating the labeling and nutritional claims of the product,
Detecting contaminants and adulterants,
Improving recordkeeping and audit preparation.

While UV-Vis is a reliable screening technique, users should remain aware of the limitations of UV-Vis spectrophotometry particularly concerning its sensitivity, specificity and potential for matrix effects. Ultimately, UV-Vis spectrophotometry enhances food safety, builds consumer confidence and enables continuous development of food quality control systems within the global supply chain.

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ECONOMIC MILLET PRODUCTION, FUNCTIONAL FOOD AND HEALTH BENEFIT

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Abstract: Millets is an alternative cereal. Functional food, rich in protein, vitamins, minerals, nutrients, and energy. Millet is a highly nutritious and climate-adapted crop. Although millet food products are known for their nutritional value, consumer awareness is low, especially regarding their nutritional and therapeutic benefits. Millet does not contain gluten, making it a useful grain in the diet of people with celiac disease. Millet is a rich source of fiber, nutrients, minerals, B-complex vitamins and phytochemicals such as polyphenols, lignans, phytosterols, phytoestrogens, and phytocyanins. High fibre content and the presence of some anti-nutritional factors such as phytate and tannin in millet affect the bioavailability of minerals. The economic and health benefits of millet are explained in detail in this study. The production of millet in the world is showing an increasing trend. The world area of millet in 2023 was 31.3 million ha, with a yield of about 1.0 t ha⁻¹ and a total production of 31.6 million tons. Millet has numerous health benefits. Millet phytochemicals: polyphenols, lignans, phytosterols, phytoestrogen, phytocyanin, act as antioxidants, immunomodulators, detoxifiers, etc. and therefore protect against degenerative diseases associated with aging, such as cardiovascular disease (CVD), diabetes, cancer, etc. Consuming millet can help reduce liver disease.

Keywords: *Panicum miliaceum* L., Production, Yield, Functional food, Health advantage

INTRODUCTION

Panicum miliaceum L., or proso millet, is an annual grass. It is said to have originated in the Central areas of Europe as early as 2000 B.C. Dry conditions like those found in central Russia, the Middle East, northern India, Africa, Manchuria, and the Great Plains region of North America are particularly ideal for this plant. First brought to Canada in the 17th century, millet was rarely used as livestock feed in the early 20th century. It has been cultivated in East Asia for the last 10.000 years. Diseases are unknown, and proso millet is a comparatively low-demanding crop. For this reason, millet is often used in European organic farming methods. It is often used as an inter-cropping in the United States.

Continuous crop rotation is possible with millet, which can help prevent a summer fallow. Proso millet is a useful intercrop between two crops that require water and pesticides because of its superficial root system and tolerance to atrazine residue. Millet grows more quickly and earlier because the stubbles of the previous crop enable more heat to enter the soil. Throughout human history, millet have been significant food mainstays, especially in Asia and Africa. For generations, millets have been vital staples in the semi-arid tropical regions of Asia and Africa. For millions of the poorest people in these areas, millets continue to be their main source of protein, energy, vitamins, and minerals. Millets are cultivated under severe conditions that hinder the growth or productivity of other crops. They are cultivated using scarce water resources (Popović et al., 2025a).

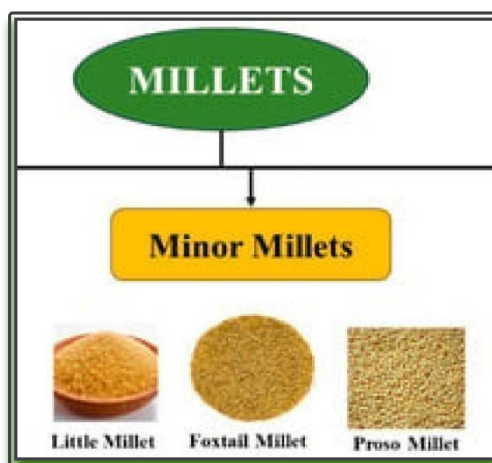
Modern plant production is becoming more and more reliant on cutting-edge technological solutions that enhance nutritional value and productivity. Through intelligent crop management, new agricultural technology, particularly smart agriculture and precision farming methods, allow farmers to maximize resource allocation and enhance the nutritional profile of cereal grains.

The development of superior grains that satisfy the increasing customer demand for functional foods with improved health benefits is made possible by this technical advancement (Popović et al., 2013; 2020a,b; Pejanović et al., 2024a,b; Pejanović and Urekar, 2025; Popović, 2025; Pejanović and Ergunova, 2025).

Because they contain vitamins, minerals, and bioactive compounds that promote human health and recovery, millets (*Panicum* sp.) are adaptable, small-grained grains of therapeutic importance. Millets include both large millets like finger millet and pearl millet and small millets like foxtail millet, little millet, kodo millet, proso millet, brown top millet, fonio, teff, and barnyard millet, Picture 1. A significant growth in knowledge of millets' nutritional benefits has led to an increase in demand for millets like food and value-added products. Millets include roughly 65-75% carbohydrates, 7-12% proteins, 2-5% fat, and 8-15% fibre. They have more essential amino acids than typical cereals, and millets' prolamin facilitates the digestion of proteins (Bhattacharya, 2023). The therapeutic potential of millets needs to be considered. Eating millet has been shown to enhance glycaemic control, reduce body mass index (BMI), halt the progression of pre-diabetes, and reduce the risk of atherosclerotic cardiovascular disease (Geetha et al., 2020; Popović et al., 2020a, 2022, 2024, 2025a,b).

Millet are helpful dietary grains since they are gluten-free. Fibre, minerals, and B-complex vitamins are abundant in millet. The bioavailability of minerals is impacted by millets' high fibre content and the presence of some anti-nutritional elements like phytates and tannins. Few human investigations have indicated that millet tend to absorb less iron than rice or even wheat. Oxidative stress is now recognized as an important etiological factor in the causation of several chronic diseases including cancer, cardiovascular diseases, osteoporosis, and diabetes. Antioxidants play an important role in mitigating the damaging effects of oxidative stress on cells. Lycopene, a carotenoid antioxidant, has received considerable scientific interest in recent years (Rao et al., 2006; Popović et al., 2025a). Phytochemicals that promote health, such as polyphenol, lignan, phytosterol, phytoestrogen, and phytocyanin, are also abundant in millet. These defend against age-related degenerative diseases like cancer, diabetes, and cardiovascular disease (CVD) by acting as

antioxidants, immunological modulators, detoxifying agents, etc. (Rao et al., 2006, 2007). In addition to their established roles in avoiding diseases caused by dietary deficiencies, certain of the well-known nutrients' vitamins, minerals, and essential fatty acids also offer advantages in terms of preventing degenerative diseases. Millet is safe for those with celiac disease and gluten allergies because they are non-glutinous.



Picture 1. Little Millet, Foxtail Millet and Proso Millet

They don't generate acid, are simple to digest, and don't cause allergies (Saleh et al., 2013). Millet may offer protection against degenerative disorders that develop with ageing. Eating millet lowers the risk of heart disease, prevents diabetes, enhances the digestive system, lowers the risk of cancer, detoxifies the body, boosts immunity in respiratory health, boosts energy, improves the muscular and neural systems, and protects against a number of degenerative diseases, including Parkinson's disease and metabolic syndrome (Manach et al., 2005; Scalbert et al., 2005; Chandrasekara and Shahidi, 2011, 2012). Resistant starch, oligosaccharide, lipids, and antioxidants like phenolic-acids, avenanthramide, flavonoid, lignan, and phytosterol are among the significant nutrients found in millet. These nutrients are thought to be responsible for numerous health benefits (Miller, 2001; Edge et al., 2005; Popović et al., 2022). The purpose of this study is to highlight millet production as a significant functional food and to show how millet affects health. The aim of the research was to show the production of millet in the world and in our country and to point out the importance of millet as a functional food.

MATERIAL AND METHODS

FAO 2025 data on millet production in our nation and globally is used in the study (FAO 2025; www.fao.org/faostat/en/#data/QCL). Additionally, the literature and other materials from congresses, symposiums, and conferences that addressed the issue of millet production under study were used. Descriptive statistics were used to process all the data. The analyzed data is shown in tables and figures to make the features under investigation plainly evident.

RESULTS AND DISCUSSION

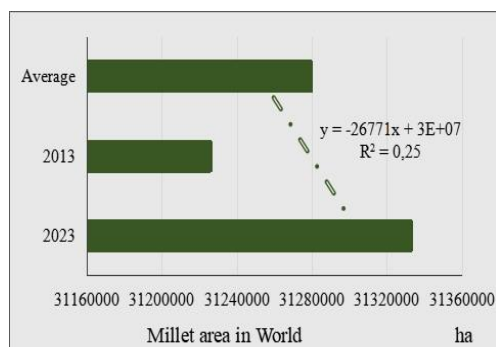
Global Cereals Production

Millet are important staples to millions of people worldwide. These are rain fed crops grown in areas with low rainfall and thus resume greater importance for sustained agriculture and food security. Almost all millets are used for human consumption in most of the developing countries, but their use has been primarily restricted to animal feed in developed countries. The average area sown with millet and the average millet production in the world and in Serbia is showing a growing trend, Table 1, Figures 1a and 1b and Figures 3a and 3b. The average area sown with millet is increasing globally, in 2023 the area was 31.322.668 ha and was higher than in 2013 (31.225.586 ha) (Table 1). Appropriate growing techniques, climatic conditions and variety selection are key to profitable millet production.

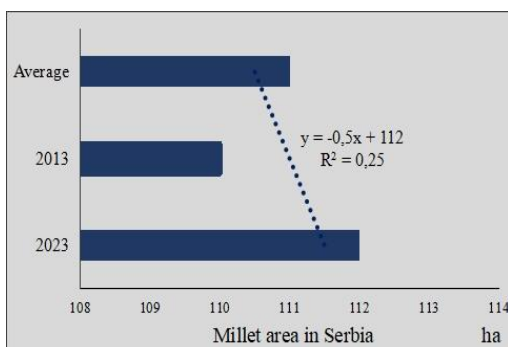
Table 1. Parameters of millet production in the world, 2023

Parameter	World	Serbia	Share in the world (%)	
Year	Area (ha)			
2023	31332668	112	0.0004	
2013	31225586	110	0.0004	
Average	31279127	111	0.0004	
	Production (t)			
2023	31596316	107.0	0.0004	
2013	26423961	150.0	0.0006	
Average	29010139	128.5	0.0005	
	Yield (kg/ha)		Increase (kg)	Increase (%)
2023	1008	955,0	53.0	5.5
2013	846.2	1363.6	517.4	61.1
Average	927.1	1159.3	232.2	25.1
IV	161.8	408.6	-	-

In the world in 2023, millet grain yields were lower by 161.8 kg compared to 2013, or 19.1%, Table 1, Figure 2a. Average yields in Serbia in 2013 were significantly higher (1363.6 kg/ha) compared to 2023 (955 kg/ha), or 42.7% or 408.6 kg/ha, Table 1, Figure 2b.

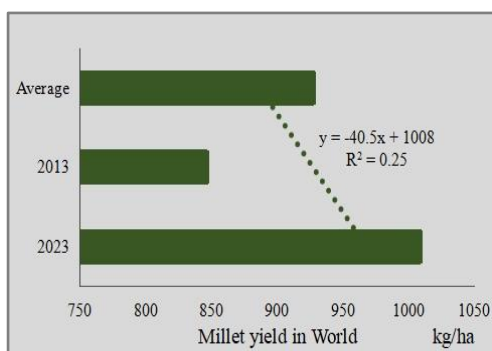


a.

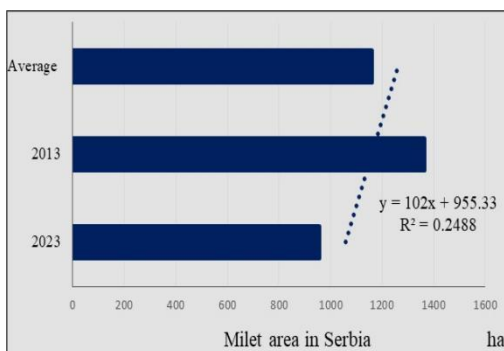


b.

Figure 1. Millet area in world (a.) and in Serbia (b.)

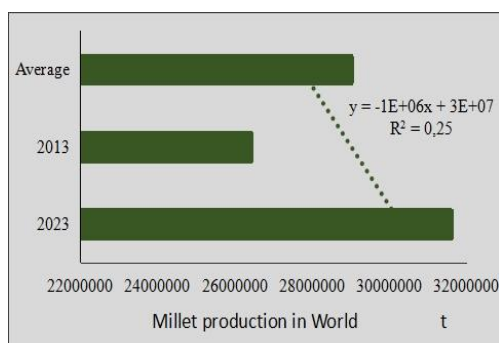


a.

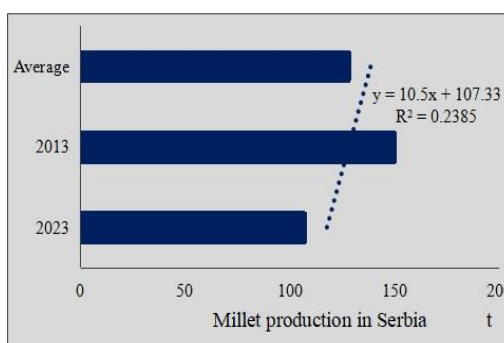


b.

Figure 2. Millet grain yield in world (a.), and in Serbia (b.)



a.



b.

Figure 3. Millet production in world (a.), and in Serbia (b.)

Both the amount of precipitation in shorter time intervals and the frequency of extreme (dry) periods throughout the year have increased. Climate change adaptation strategies are becoming more and more crucial in this context (Popović et al., 2025a,b).

Sustainable food production systems guarantee future food production while addressing the requirement to expand food production on current agricultural land in ways that do not negatively impact the environment. The aforementioned suggests that cereals are crucial to our nation's economic and food security, and that advancing production technologies and adjusting to new problems are critical considerations (Popović et al., 2025a,b).

Millet's Chemical Composition

Millet is nutritionally comparable to major cereals and serves as a good source of protein, micronutrient and phytochemical. Processing methods like soaking, malting, decortication, and cooking affect the antioxidant content and activity (Saleh et al., 2013). While sorghum and most of the millets contain about 10% protein, 3.5% lipids, finger millet contains 12-16% protein and 2-5% lipids. Millet are very good sources of micronutrients such as vitamins and minerals. Major portion of sorghum protein is prolamins (kaffirin) which has a unique feature of lowering digestibility upon cooking whereas, the millet has a better amino acid profile. Millet contain fewer cross-linked prolamins, which may be an additional factor contributing to higher digestibility of the millet proteins. For both people and domestic animals, millet is a crucial component of a comprehensive, functioning diet.

They serve a variety of functions, such as raw materials for human nourishment (flour, bread, oil, beer, soft drinks), animal feed, coarse food (i.e., animal feed), a source of bedding or straw for animal breeding, mulching, and the generation of bioethanol, among other uses. The principles of organic agriculture make millet suited for production. Because of its many applications, suitable chemical makeup, and researched growing methods, millet is considered a vital source of both human and animal protein and energy. After a complicated industrial processing procedure, millet can be used to manufacture a variety of food products, such as flakes, groats (semolina), different confections, and more. The average nutrient composition of some millet grains is summarized in Table 2. Millet's chemical makeup varies greatly (Table 2, Figure 4). About 12.5% of protein is present in millet, 70% carbohydrates, 15% dietary fiber, 2.5-3.5% minerals, and good source of phosphorous and iron, Table 2.

Table 2. Chemical composition of millet *Panicum miliaceum* L.

Parameter	Energy	Protein	Carbohy drates	Oil	Dietary Fiber	Minerals	Copper	Phosphorus	Iron
	KJ			g				mg/100g	
Millet	341	12.5	70.05	2.2	15.1	2.5	1.6	206	10.1

Finger millet contains roughly 5-8% protein, 65-75% carbs, 15-20% dietary fibre, and 2.5-3.5% minerals (Chethan and Malleshi, 2007; Chethan et al., 2008). Epidemiological studies have demonstrated that regular eating of whole grain cereals and their products can reduce the incidence of cardiovascular disease, gastrointestinal disorders, and diabetes mellitus (McKeown, 2002).

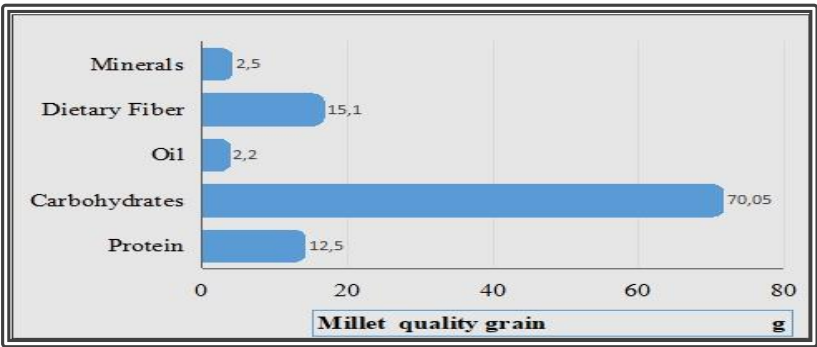


Figure 4. Millet grains quality composition (g)

When millet is used as whole grains, the vital nutrients such as dietary fibre, minerals, phenolics, and vitamins concentrated in the grain's outer layer or seed coat become part of the food and provide its nutritional and health advantages (Antony et al., 1996). In addition to having nutritional characteristics like those of main cereals, millet are excellent suppliers of carbohydrates, minerals, and phytochemical with nutraceutical qualities.

Compared to maize, millet protein has superior essential amino acid profiles. While finger millet proteins are distinct due to their sulfur-rich amino acid composition, pearl millet has a greater niacin level than any other crop. Millet proteins are low in lysin, much like cereal proteins, but they work well with lysin - rich vegetable (leguminous) and animal proteins

to create nutritionally balanced composites with high biological value. When it comes to nutrition, little millets are superior to fine cereals (Popović, 2025a).

Millet is a staple food for many cultures in Asia and Africa and are grown in arid and semi-arid parts of the planet. Because they are high in vitamins and minerals, they are known as *nutricereals*. Additionally, because millet contain advantageous phytochemicals that offer medicinal properties for a range of ailments, they have nutraceutical relevance. A wide variety of biological compounds can be found in both plant parts and grains. Eating millet has been shown to be beneficial for lifestyle and metabolic illnesses. Two methods to assess millets' therapeutic potential include the existence of phytochemicals and speciality compounds like flavonoid, phenolic, anthocyanidin, and others with antioxidant capacity, as well as additional nutrition through minerals and vitamins. Millet has a low glycaemic index, are gluten-free, and contain phytochemicals that help treat lifestyle problems and prevent diseases like cancer. Additional benefits include treatment for anaemia and calcium deficits, especially in young children and pregnant people (Stevanović et al., 2023, 2024; Popović et al., 2025a,b). Amino acids, particularly those containing sulphur, like cysteine and methionine, are abundant in millet. Millet species are a great source of essential amino acids since they have a high proportion of methionine in addition to lysine and threonine (Saleh et al., 2013). Compared to rice, sorghum, and maize, millet has higher lipids (Obilana and Manyasa, 2002). The protein content of millet grains is influenced by both genetic and environmental variables, especially the availability of nitrogen fertilizers (Dragičević et al., 2014). The nutritional profile of cereals is greatly impacted by agronomic practices. Numerous agronomic practices, including fertilization, weed control, nitrogen regulation, and varietal selection, have a significant impact on millet's nutritional composition. These techniques improve the macro-nutrient and micro-nutrient levels of the grain while also increasing its overall yield and quality.

Benefit of Millet

A useful food is millet. Beyond their nutritional value, functional foods which contain vitamins or other additional ingredients offer health benefits. Millet is supplemented with fibre, vitamins, minerals, and probiotics. In addition to their primary nutrients, millet have therapeutic qualities due to the presence of phenolic compounds, the predominant form of secondary metabolites. Lignins, polyphenols, phytocyanins, phytoestrogens, and phytosterols are among them. These compounds protect genetic material and cellular membranes by functioning as antioxidants. Numerous health-promoting and protective properties, such as antimicrobial, immuno-modulatory, anti-inflammatory, antiviral, anticancer, antiplatelet aggregation, and inhibitory activities on digestive enzymes and cataract formation, have been associated with millet phenolics (Viswanath et al., 2009; Shobana et al., 2009).

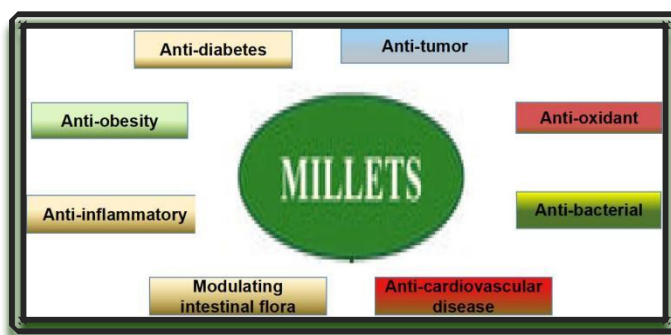
Polyphenols exist in both bound and unbound forms. The pharmacological activities of bound polyphenols include antioxidant, anticancer, immunomodulatory, antifungal, and anti-hyperglycemia characteristics (Shi et al., 2010), Picture 2. Protein glycation, protein aggregation formation, oxidative DNA damage, and hydroxyl radical-induced protein fragmentation are all prevented by millet phenolics (Anis and Sreerama, 2020). Chethan et al. (2008) identified nine phenolic acids, including gallic acid, protocatechuic acid, p-hydroxybenzoic acid, vanillic acid, ferulic acid, syringic acid, trans-cinnamic acid, and p-

coumaric acid, in millets. Hydroxycinnamic acids and their derivatives were the main contributors to the total phenolic compounds of the insoluble-bound phenolic fraction of millet varieties, according to Chandrasekara and Shahidi (2011).

One of the most prevalent hereditary disorders is celiac disease (CD), which is caused by a reaction to gluten proteins in wheat and other cereals in those who are genetically predisposed. This illness, which can produce excruciating stomach pains, is brought on by the immune system's negative response to gluten. Because millet is gluten-free, it can be a nutritious diet for people with celiac disease (Carolina et al., 2007).

It is well known that millet grains are high in phytate, tannins, and phenolic acids (Thompson, 1993). According to Graf and Eaton (1990), these nutrients lower the risk of breast and colon cancer in mice. Compared to people who eat wheat or maize, sorghum and millet have a lower incidence of esophageal cancer due to their fibre and phenolic content (Van Rensburg, 1981). Fibre is one of the greatest and simplest strategies to stop women from developing breast cancer, according to recent research. Millet's anti-carcinogenic qualities are widely known.

Antioxidant Properties and Detoxification Many of the antioxidants in millet have a positive effect on removing other toxins from the body, such as those in the kidney and liver, and neutralizing free radicals, which can cause cancer. By encouraging appropriate excretion and neutralizing enzymatic activity in those organs, quercetin, cucurmin, ellagic acid, and other advantageous catechins can aid in the removal of any foreign substances and poisons from the body. Because of their functions in human health, polyphenols have received a great deal of interest (Tsao, 2010).



Picture 2. Millets health benefit

Zhang et al. (2014) examined the phytochemical makeup, antioxidant capability, and anti-proliferative characteristics of three millet cultivars. In vitro studies were conducted to examine anti-proliferative properties against MDA human breast cancer and HepG2 hepatocellular carcinoma. The results show that millet has some anti-proliferative qualities. Consuming millet lowers cholesterol and phytate, which are associated with a higher risk of cardiovascular disease and cancer. Essential phytonutrients included in millet, known as lignans, lower the risk of heart disease and help prevent hormone-dependent malignancies, such as breast cancer. Postmenopausal women with high blood pressure and cholesterol can benefit from regular millet consumption (Shahidi and Chandrasekara, 2013; Saleh et

al., 2013; Changmei and Dorothy, 2014). Millet helps prevent age-related illnesses and slows down the ageing process (Pathak, 2013; Shahidi and Hadrsekara, 2013).

Given this, it is reasonable to expect that it will be effectively addressed in international economic relations and development policy. This would enable output to grow sustainably, boost exports, and be free of imports all of which are made feasible by favourable, even extraordinary, conditions in the country (Lakić et al., 2022; Milunović et al., 2022; Ljubičić et al., 2023; Popović et al., 2020a,b, 2023, 2024, 2025a,b). Over the past century, some cereals have been referred to as functional, biologically superior, and nutritionally superior dietary goods that improve certain elements of health. The main reasons for the rise in interest in functional foods are the effects of industrialisation and urbanisation on lifestyle, demographic changes (population ageing, especially in developed countries), the disappearance of traditional eating habits, and awareness of the negative health effects of urban living (Kaur and Singh, 2017; Ameratunga et al., 2016). Due to its lack of gluten, millet (*Panicum miliaceum* L.) is a grain that is becoming more and more popular. It was consumed 10.000 years ago in China (Lu et al., 2009) and roughly 4.000 years ago in central Europe. The areas of Russia, Eastern Europe, northern India, and some portions of Africa are where it is most commonly grown. According to recent studies, millet's functional significance in human nutrition is growing (Dykes and Rooney, 2006; Kalinova and Moudry, 2006; Zarnkow et al., 2007). Essential amino acids (leucine, isoleucine, and methionine) (Kalinova and Moudry, 2006), proteins (13 g/100 g dry matter), carbs (72 g/100 g dry matter), polyphenols (phenolic acids and flavonoids), and a high concentration of minerals and dietary fibre are all found in millet (Ravindran, 1991). The aforementioned suggests that millet may be used in nutrition as a component that enhances functionality. It also suggests that it is necessary to investigate the chemical composition and elucidate the possibility of using millet in nutrition as a component that enhances the functionality of specific nutritional products.

CONCLUSION

Because millet has a number of useful components, such as water-soluble fibre, oligosaccharide, and resistant starch, it can be used to create a wide range of products with different purposes and health benefits. There is a developing tendency in the millet area. With an average millet area of 31.32 million hectares worldwide and a yield of 1 t/ha, 31.596.316 t of millet were produced in 2023. There are numerous health benefits of millet. Eating millet may help reduce liver disease, according to several studies. Millet's lignan aid in the prevention of heart disease and some hormone-dependent malignancies, including breast cancer. The metabolism of cholesterol is positively impacted by millet proteins. HDL cholesterol levels in plasma rise after millet protein is digested. Plant breeders should choose millet for better health benefits in addition to raising yields.

ACKNOWLEDGMENT

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is also the result of a technical solution: Technological process of millet - *Panicum miliaceum* L. organic production to obtain gluten-free grain, raw material for functional food. / Tehnološki postupak organske proizvodnje prosa (*Panicum miliaceum* L.) za dobijanje bezglutenskog zrna, sirovine za funkcionalnu hranu.

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NON-HERBICIDE SOLUTIONS AS A POSSIBLE ALTERNATIVE IN WEED CONTROL

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Abstract: We investigated the effectiveness of non-herbicidal agents to control weeds in sugar beets. Experiments were performed under field and laboratory conditions. We monitored the level of effect of 50, 70 and 100% solutions of vinegar, and alcohol, also 50, 70 and 100°C hot water, and an open flame. The sensitivity/efficiency under laboratory conditions was tested by analyzing the changes in the chlorophyll content of weeds (*Abutilon theophrasti*, *Chenopodium album*) and sugar beet plants. The obtained results indicate that any method of weed control in sugar beet is acceptable, especially when aiming to reduce the use of herbicides. Application of flame (with shields) was shown to be the safest alternative weed control measure. Weeds and sugar beet plants are sensitive to treatments with alcohol, vinegar, flame and hot water as measured by chlorophyll content.

Keywords: Non-herbicides, Sugar beet, Weed, Chlorophyll

INTRODUCTION

Sugar beet is grown in Serbia on 60.000-75.000 ha. The highest production is achieved by producers in the territory of Srem (51 t/ha), and the lowest in Banat region (33 t/ha) (www.plodnazemlja.com). However, similar to the rest of Europe, there is a decline in sugar beet production (<14%) and in planted areas (7%) each year (www.cefs.org). In addition to financial constraints, this trend is driven by climate change, reduced use of pesticides and synthetic fertilizers, and the declining availability of effective pesticide options (development of resistance, list of prohibited active substances, etc.).

Recently, Serbia has experienced prolonged drought in addition to record-high average daily temperatures (July and August) affected dry leaf and root weight, total dry weight, net assimilation rate, specific leaf area etc. (Albayrak and Çamas, 2007).

High temperatures and poor distribution of precipitation affect the metabolic processes in sugar beet, while the presence of weeds suppresses plant growth and development, particularly root growth and the biosynthesis of soluble sugars (Seadh et al., 2013). Therefore, selected and timely applied methods of weed control, especially in the first eight

weeks after sowing, significantly affect the sugar beet (Zoschke and Quadranti, 2002; May and Wilson, 2006).

Producers have long relied on the application of herbicides as the safest way to eliminate weeds and achieve high yields. Today, minimal or zero tolerance for the use of pesticides, concern for the environment and the goal to produce health-safe food limits the use of herbicides in sugar production (EPA, 2025). Considering these challenges, it is necessary to react quickly by applying new technologies, innovative solutions and adopt agricultural practices in order to minimize the negative effects.

In addition to the above, the introduction of alternative weed control measures: inter-row cultivation, harrowing, mulching, hoeing, growing mixed crops, crop rotation, application of flames, application of hot water, innovative technologies, bioherbicides, etc. provides one of the sure ways to control weeds.

The aim of this work was to examine different alternative methods of weed removal in sugar beet crops.

MATERIAL AND METHODS

In the production unit of the company “Carnex doo” in Bačko Dobro Polje in the South Bačka District, Serbia, Southeast Europe, the cultivar “Eduarda” KWS of sugar beet was established for the field part of the experiment. The experiments were conducted under laboratory and field conditions in 2024. Laboratory tests were performed at the Institute for Plant Protection and Environment (Belgrade, Serbia). The tested treatments under field conditions are shown in Table 1. The list of treatments applied under laboratory conditions is shown in Table 2.

Table 1. Experimental design (field)

<i>Treatment</i>	<i>I</i>	<i>II</i>	<i>III</i>
Crop	BBCH 14	BBCH 14-16	BBCH 16-18
Weed	Ponici + 2 lista	Korovi 2-4 lista + p	Korovi 4-6 listova + p
Date	13.4.2024.	28.4.2024.	13.5.2024.
K1	-	-	-
K2=T6	Powertwin 1 l/ha + Hemomitron 1 l/ha + Safari 30 g/ha + Trend 100 ml/ha	Powertwin 1,5 l/ha + hemomitron 1,5 l/ha + safari 30 g/ha +Trend 100 ml/ha	Powertwin 1,5 l/ha + Hemomitron 1,5 l/ha + Safari 30 g/ha + Loret 0,2 l/ha + Trend 100 ml/ha
T7	Cultivator	Alcohol 1:3, 65 l/ha	Alcohol 1:3, 130 l/ha
T8	Cultivator	Vinegar, 200 l/ha	Vinegar, 200 l/ha
T9	Cultivator	Hot water, 200 l/ha	Hot water, 200 l/ha
T10	Cultivator	Open flame	Open flame

Table 2. Experimental design (laboratory)

	<i>Alcohol</i>	<i>Vinegard</i>	<i>Hot water</i>	<i>Flame</i>
Weeds and sugar beet	50%	50%	50 ⁰ C	propane-butane gas
	70%	70%	70 ⁰ C	
	100%	100%	100 ⁰ C	

Application of the flame in the field was carried out at an angle of 45 degrees (with a shield), at a height of 15 cm. Solutions of alcohol, water and vinegar applied with „Solo“ sprayer (20 L).

Laboratory experiments

The efficacy was tested on weed species under laboratory conditions on the most abundant weed species collected in the field: *Abutilon theophrasti* and *Chenopodium album*. Application of non-chemical agents was done using a hand sprayer in concentrations of 50, 70 and 100% (alcohol, vinegar), 50, 70 and 100°C hot water and a flame.

Sugar beet and weed plants were grown from seed under controlled conditions (12:12h day:night, T=22/16°C day and night, watering as needed).

Weed plants were treated when they developed 2 leaves. Efficacy was evaluated 14 days after the treatment. The treatment of sugar beet plants was done at 7, 14, 21, 28 and 35 days after the emergence and the sensitivity assessment was done 14 days after application.

In all species, the efficacy of the applied treatments was assessed by measuring the content of chlorophyll *a*, *b* and total chlorophyll.

Chlorophyll extraction

Extraction of chlorophyll was done by liquid nitrogen from plant leaves (0.5 g). Methanol (5 mL) was added to each sample, centrifuged at 1500 rpm for 10 min before measurement and analyzed on a spectrophotometer (UV 2100, Shimadzu). The absorption of chlorophyll *a* was read at $\lambda = 653$ nm, chlorophyll *b* at $\lambda = 666$ nm and carotenoids at $\lambda = 470$ nm. The content of chlorophyll (total, *a*, *b*) was calculated according to the formulas given by Wellburn (1994).

Statistics: The number of weeds and the evaluation of the effectiveness of the applied methods under field conditions were performed 14 days after the treatment and shown as a percentage compared to the control (K -number of weeds in the variant/ $K \times 100$). Analysis of the obtained data for the extracted chlorophyll was performed by analysis of variance ANOVA (LSD test) and t-test in the Statistica 7 package.

RESULTS AND DISCUSSION

Field experiment

Based on the analysis of the results in Table 3, it can be concluded that the application of hot water showed the lowest level of efficacy on the present weed species (4.25-12.07%), while the application of herbicides showed the highest level of efficacy (76.78-94.12%). In the control of species *Abutilon theophrasti* and *Ambrosia artemisiifolia*, the application of herbicides showed satisfactory efficacy, while the application of alcohol, hot water and vinegar showed poor efficacy. The use of flames has proven to be an alternative method that, under conditions without the use of herbicides, can help the crop in competition with weeds. Control of *Chenopodium album* species was only good after the application of

herbicides, while in the control of *Chenopodium hybridum* the application of flames achieved the level of efficacy over 50%. Control of *Datura stramonium* was good after herbicide application and satisfactory after the flame application. Control of *Solanum nigrum* was good after herbicide application and satisfactory after the flame application (Table 3).

Table 3. Efficiency (%) of non-herbicides tested in the field 14 days after treatment

	<i>Herbicides</i>	<i>Alcohol</i>	<i>Vinegar</i>	<i>Hot water</i>	<i>Flame</i>
	<i>Efficacy (%)</i>				
<i>Abutilon theophrasti</i>	78.89	26.76	17.78	8.89	35.55
<i>Ambrosia artemisiifolia</i>	76.78	25.89	21.43	7.14	53.57
<i>Chenopodium album</i>	91.49	17.02	13.83	4.25	36.17
<i>Chenopodium hybridum</i>	91.38	36.21	24.14	12.07	51.72
<i>Datura stramonium</i>	94.12	47.06	32.35	11.76	76.47
<i>Solanum nigrum</i>	93.02	30.23	17.44	11.63	76.74

Laboratory experiment

It can be stated that the efficacy under laboratory conditions is similar to the efficacy determined under the field conditions. Analysis of the effect of the tested non-herbicide solutions under laboratory conditions showed that the effectiveness compared to the control is very weak, except for the use of open flame (Table 4). Visual damage was observed only under laboratory conditions on the plants after the application of 70-100% vinegar and an open flame.

Table 4. Efficacy (%) of non-herbicides 14 days after treatment on weeds and sugar beet in the laboratory

	<i>Chenopodium album</i>	<i>Abutilon theophrasti</i>	<i>Sugar beet</i>
	<i>Efficacy (%)</i>		
Alcohol 50%	17%	0%	
Alcohol 70%	75.22	30%	
Alcohol 100%	100%	35%	
Vinegard 50%	12.25%	0%	
Vinegard 70%	15%	7.5%	selective
Vinegard 100%	15.65%	10%	
Hot water 50°C	0%	0%	
Hot water 70°C	8.25%	0%	
Hot water 100°C	10%	5%	
Open flame	100%	80%	80-90%

Contrary to the efficacy in the field and laboratory, the analysis of chlorophyll (*a*, *b* and total) content showed the sensitivity of both weeds and sugar beet to non-herbicide solutions (Tables 5, 6, 7). *Chenopodium album* plants were especially sensitive to 100% alcohol and 50,70 and 100% vinegar (total damage).

Table 5. Chlorophyll *a* content in weed plants

	<i>Chenopodium album</i>	<i>Abutilon theophrasti</i>
C - Alcohol 50%	0.000**	0.000**
C - Alcohol 70%	0.000**	0.000**
C - Alcohol 100%	0	0.000**
C - Vinegard 50%	0	0.000**
C - Vinegard 70%	0	0.000**
C - Vinegard 100%	0	0.000**
C - H.Water 50°C	0.000**	0.000**
C - H.Water 70°C	0.000**	0.000**
C - H.Water 100°C	0.000**	0.000**
C - Open flame	0	0.000**
SD	0.97	1.573
mean	1.03	2.706

C-control, sd-standard deviation, p<0,05*, p<0,01**, efficacy 14 days after treatment

Table 6. Chlorophyll *b* content in weed plants

	<i>Chenopodium album</i>	<i>Abutilon theophrasti</i>
C - Alcohol 50%	0.000**	0.000**
C - Alcohol 70%	0.000**	0.000**
C - Alcohol 100%	0	0.000**
C - Vinegard 50%	0	0.000**
C - Vinegard 70%	0	0.000**
C - Vinegard 100%	0	0.000**
C - H.Water 50°C	0.004**	0.000**
C - H.Water 70°C	0.000**	0.000**
C - H.Water 100°C	0.000**	0.000**
C - Open flame	0	0.000**
SD	0.376	0.607
mean	0.390	0.850

C-control, sd-standard deviation, p<0,05*, p<0,01**, efficacy 14 days after treatment

Table 7. Total chlorophyll content in weed plants

	<i>Chenopodium album</i>	<i>Abutilon theophrasti</i>
C - Alcohol 50%	0.000**	0.000**
C - Alcohol 70%	0.000**	0.000**
C - Alcohol 100%	0	0.000**
C - Vinegard 50%	0	0.000**
C - Vinegard 70%	0	0.000**
C - Vinegard 100%	0	0.000**
C - H.Water 50°C	0.000**	0.000**
C - H.Water 70°C	0.000**	0.000**
C - H.Water 100°C	0.000**	0.000**
C - Open flame	0	0.000**
SD	1.335	2.113
mean	1.42	3.557

C-control, sd-standard deviation, p<0,05*, p<0,01**, efficacy 14 days after treatment

Analysis of the chlorophyll content in sugar beet plants after the application of non-herbicidal solutions showed that they are sensitive to the application of alcohol, vinegar,

hot water, and flame. High sensitivity (based on the content of chlorophyll *a* and *b*) under laboratory conditions is observed after the flame application (youngest plants), 100 % vinegar (plants old 14 and 28 days), 100% alcohol (plants old 35 days) (Table 8). Statistical analysis of the sensitivity of sugar beet plants treated at different stages of development is shown in Table 8.

Table 8. Total chlorophyll content in sugar beet plants

Plant age	7 days old	14 days old	21 days old	28 days old	35 days old
IV efficacy					
C - Alcohol 50%	ns	0.000**	0.000**	0.000**	0.000**
C - Alcohol 70%	0.000**	0.000**	0.000**	0.000**	0.000**
C - Alcohol 100%	0.000**	0.000**	0.000**	0.000**	0
C - Vinegard 50%	0.000**	0.000**	0.000**	0.000**	0.000**
C - Vinegard 70%	0.000**	0.000**	0.000**	0.000**	0.000**
C - Vinegard 100%	0.000**	0	0.000**	0	0.000**
C - H.Water 50°C	0.000**	0.000**	0.000**	0.000**	0.000**
C - H.Water 70°C	0.000**	0.000**	0.000**	0.000**	0.000**
C - H.Water 100°C	0.000**	0	0.000**	0.000**	0.000**
C - Open flame	0	0.000**	0.000**	0.000**	0.000**
SD	4.823	5.689	3.909	6.675	5.659
mean	9.613	9.854	13.613	10.551	11.455

C-control, sd-standard deviation, $p<0,05^*$, $p<0,01^{**}$, efficacy 14 days after treatment, ns-nonsignificant differences

Sugar beet as a crop is extremely demanding in terms of growing conditions. With their presence weeds affect the yield and as regular companions of cultivated plants they cause numerous negative effects: they take up living space, consume light, nutrients and water for cultivated plants (da Silva et al., 2022). New/old alternative non-herbicide weed control measures are gaining importance: mulches, flames, steam and foam, infrared rays, electric current (Jabran and Chauhan, 2018), as well as cultivation of more resistant and competitive genotypes, improvement of cultivation technology, etc. (Monteiro and Santos, 2022). The non-herbicidal treatments tested exhibited low levels of weed control under field conditions, except for the flame application. Conversely, no visual symptoms of damage were observed on sugar beet and weed plants except after the flame application. Contrary to this, damage to weed plants was observed under laboratory conditions after the application of flame and the highest concentrations of alcohol and vinegar.

However, the application under laboratory conditions showed that there are both visual and physiological symptoms of damage. In particular, the effectiveness was expected after the application of a 100% solution of vinegar and alcohol and 100°C water. Visual damage symptoms were observed after the application of 70 and 100% (4-7% vinegar in 100% solution) on the leaves of *Abutilon theophrasti* and complete decay of *Chenopodium album* seedlings.

However, analysis of the chlorophyll content showed a higher level of sensitivity (Tables 5, 6 and 7) and even a complete decay of seedlings of: *Chenopodium album* after application of 100% alcohol and 50, 70 and 100% vinegar and *Abutilon theophrasti* after the flame application. Similar results were obtained by Radhakrishnan et al. (2003). The use

of vinegar for weed control has been studied several times (Evans et al., 2009, 2011; Johnson et al., 2003; Webber III et al., 2012) and it has been shown that it can be used as a contact herbicide. Also, it was concluded that vinegar is most effective in suppressing seedlings and preventing weed seeds' germination (Owen, 2002). Webber III et al. (2018) successfully controlled *Chenopodium album*, *Abutilon theophrasti*, *Amaranthus hybridus* and *Cirsium arvense* under controlled conditions using 5, 10.5, 15.3 and 20.2% vinegar solutions. Low levels of effectiveness of vinegar under field conditions (Table 2) can be related to the climatic conditions in the open field, the use of vinegar without adjuvants and the low concentration of acetic acid in the solution (4-7%).

The effectiveness of applied hot water and flame as a possible herbicide was expected because high temperatures damage cells by expansion of intercellular water after cell rupture (few seconds at 100°C water; Peerzada and Chauhan, 2018). Also, De Cauwer et al. (2015) found that at the most early-stage broadleaf weeds are sensitive to hot water. Hwang et al. (2012) successfully controlled *Setaria viridis* using 2% ethanol (75 and 100 l/ha). The weak effectiveness of the applied alcohol in the experiments performed can be related to the fact that some alcohols (e.g. methanol) can have a stimulating effect on the growth of plants, especially C3 (wheat, *Lolium sp.*, *Poa pratensis*, etc.) (McGiffen and Manthey, 1996) or to the fact that ethanol has an inhibitory effect (slows down the growth of plants) (Miller, 2006). During the experiment, the application of flame confirmed the possibility of its use as a method for weed control, which was also documented by numerous researchers (Taylor et al., 2012; Zhang et al., 2012; Rajković, 2018).

The limiting factor of flame application is the high sensitivity of sugar beet plants, especially after application without a shield. On the other hand, none of the tested non-herbicidal agents have shown a safety level acceptable for use in sugar beet crops. Analyzing the content of chlorophyll, especially of total chlorophyll, showed that there is a decrease in the content in the treated plants compared to the control. On the other hand, the analysis of sugar beet yield and digestion in treatments where non-herbicidal agent was applied (field conditions) showed that there were no statistically significant differences compared to the control.

Although a certain level of weed control was achieved, non-herbicidal treatments remain less effective than conventional herbicide applications (Hoffman and Regnier, 2006). Also, as a function of time, one herbicide treatment has a longer effect compared to several applications of e.g. acetic acid (20 and 30% acetic acid solution, applied 3 to 5 times) (Domenghini, 2020).

Nowadays, in line with the "Green Agenda for the Western Balkans" strategy, which aims to address climate-change challenges and support the green transition, it is necessary to intensify the use of alternative weed-control measures in order to meet the requirement of zero pesticide residues in food. Long-term pesticide use has led to environmental pollution, food residues, resistance development, and other challenges (Melander and McCollough, 2021), highlighting the need for alternative weed-control strategies.

CONCLUSION

The obtained results indicate that any method of weed control in sugar beet crops is acceptable, especially when aiming to reduce the use of herbicides. Application of flame (with shields) proved to be the safest alternative weed control measure. The application of alcohol, hot water and vinegar, as non-herbicidal agents, did not affect the growth and development of weed plants in the open field vs. laboratory conditions. Based on the measurement of chlorophyll content, the tested weed species showed sensitivity to vinegar, alcohol and hot water. The species *Chenopodium album* showed greater sensitivity to the application of flame. The highest sensitivity was shown in the treatment with vinegar and 100% alcohol.

Application of non-chemical weed control measures can increase sugar beet yield and reduce herbicide use by up to 50% because even 1 weed individual/m² can reduce sugar beet root yields by up to 11% (Longden, 1989).

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RASPBERRY PRODUCTION AS THE BASIS OF SUSTAINABILITY OF FAMILY HOLDINGS IN SOME REGIONS OF SERBIA

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Abstract: Fruit growing is one of the most important branches of agriculture in the Republic of Serbia. It is particularly important for the economic development of certain regions of Serbia. It contributes to solving economic and social problems on family holdings and stimulates the development of other economic activities. Of the total used agricultural land in Serbia, orchards account for 6.05% of the area. Raspberry is a specific fruit species that stands out from other berries in terms of its economic importance and market value. The most common variety in raspberries is Willamette, which is intended for freezing, with over 90% of the share. In 2024 the area under raspberry plantations in Serbia was 18,625 ha, the production volume was 94,026 t, and the average raspberry yield was 5 t/ha and 79.582 t of raspberries were exported, worth 247.3 million euro (SORS, 2025). Of the total exported quantities of raspberries, over 98% were exported as frozen. According to indicators and assessments based on appropriate criteria, raspberry production is economically justified and profitable for producers, providing economic security and sustainability for families for whom it is the main and only source of income. This research examined the state of raspberry production in Serbia, as well as the possibility of improving business and marketing efficiency. Based on statistical and field data, production and technical standards, a calculation procedure was used to analyze the economic effects of raspberry production and marketing, as a basis for the sustainability of family holdings in certain regions of Serbia.

Keywords: Raspberry, Production, Marketing, Economic effects, Sustainability, Family holdings

INTRODUCTION

Raspberries have a long history of cultivation and development. According to legend, the scientific name of the raspberry, *Rubus idaeus*, comes from Mount Ida in Turkey (Bushway et al., 2008). Today, there are three main raspberry producing regions in the world: Russia, Europe (mainly Poland, Hungary, Serbia, Germany and the United Kingdom), and the Pacific coast of North America (British Columbia, Washington and Oregon). In eastern North America, almost all production is for the fresh market. Many other countries, such as Chile, New Zealand and Australia, also have significant production and supply the market with fresh raspberries during winter on the Northern Hemisphere (Bushway et al., 2008). The beginning of raspberry cultivation in Serbia dates back to 1880, when Serbian emigrants brought American red raspberry seedlings to the area around the city of Valjevo in Western Serbia (Milošević et al., 2025). In terms of quantity and value, it is the most

important berry fruit in Serbia. Red raspberries are easily propagated by cuttings and bear fruit early, in the second year after planting. They reach full fruit yield in the third year. Raspberry fruit is an excellent aromatic dessert fruit, with a tart and sour taste. They are used fresh and frozen, as well as for various forms of processing. The total area under raspberry plantations in Serbia in 2024 was 18.625 ha, and the average yield in 2024 was 5 t/ha (SORS, 2025). The total volume of raspberry production in 2024 was 94.026 t, which is 4.71% less than the previous year. The high growth rate of raspberry production in Western and Central Serbia is the result of the action of several factors, the most important of which are: growing demand on the world market; changing the assortment and cultivation technology; construction of new, reconstruction, expansion and modernization of existing cold storage facilities; organized appearance of leading Serbian export companies on the markets of Western Europe and America, etc. Rural areas of Serbia face serious economic challenges, including depopulation, low level of investment and limited access to infrastructure. These areas also have the potential for the development of agriculture in line with sustainable development (Vučić et al., 2025). The concept of agricultural development has been extended to sustainable agricultural and rural development (Sustainable agricultural and rural development, SARD) concept (Stojanović and Manić, 2009; Ristić, 2013). Raspberry production is the backbone of rural development in the hilly and mountainous regions of western Serbia (Glišić and Milošević, 2017; Milićević and Đurić, 2018).

Raspberry production in Serbia is concentrated in the western part of the mountainous area, i.e. in two main production regions: West Moravian (West Morava valley) and Podrinje-Kolubara (Drina and Kolubara valleys). In the first region, most of the production takes place in the vicinity of Arilje, and in the second, in the vicinity of Valjevo (Petrović et al., 2004). The economic importance of raspberries is determined by several important factors: the high and diverse use value of the fruit; high rate of profitability in favorable agroecological conditions; high product quality; supplementary employment of labor force and indirect impact on overall socio-economic development; raspberry honey production and so on (Petrović and Milošević, 2002). Raspberries are excellent for making jams, concentrations, juices, wines and other products (Read, 2023). The secret to the success of Serbian red raspberries lies in their production in small patriarchal-family plantations. These plantations are on average only 0.36 ha and rely on hand harvesting (Glišić and Milošević, 2017).

The subject of research in this paper is the area under raspberry plantations, production volume, average yield in the world and Serbia, producer and purchase prices, profitability of raspberry production, as well as the foreign trade balance of raspberries in Serbia in the last ten-year period. The aim of the research is to determine the economic justification of investments in establishing 1 ha of raspberry plantations, profitability and the possibility of improving raspberry production and marketing, as the basis for the sustainability of family holdings in certain regions of Serbia.

MATERIAL AND METHODS

Data from several sources were used for research in this paper. Areas, volume of production and average yield of raspberries in the world and in Serbia, export, import and foreign trade balance of raspberries in Serbia, for the last ten-year period 2014-2023, were analyzed

based on statistical data collected from database sites Food and Agriculture Organization (FAO) and Statistical Office of the Republic of Serbia (SORS), website of the Ministry of Agriculture of Serbia and other relevant institutions. Also, based on the database of the System Market Information Agriculture of Serbia, producer prices and selling prices of raspberries on markets in Serbia were analyzed. According to data collected from producers through interviews from the area of Western Serbia, as well as professional standards, an economic analysis was made and financial indicators of raspberry production per unit area were determined. From the economic indicators, the amount of investments for the establishment of plantations and the fattening period of two years, the average annual financial result of raspberry production, the accumulative rate of invested capital, the economy of production and the return period of the investments made were determined. The results are presented in a table, and according to the appropriate criteria, an assessment is given on the profitability and economic justification of raising and exploiting raspberry plantations.

RESULTS AND DISCUSSION

Raspberry production in the world and Europe - Raspberry is the most important berry fruit in the world, after strawberries and blackcurrants (Milošević et al., 2025). The areas, production volume, average yield in the world and indices of changes by individual years compared to the base year, during the period 2014-2023, are set out in Table 1.

Table 1. Areas and indices, volume of production, average yield of raspberries in the world and indices of change by year, during the period 2014-2023

Year	Area		Production volume		Average yield	
	ha	Index (2014=100)	t	Index (2014=100)	t ha ⁻¹	Index (2014=100)
2014	94,636	100.00	639,022.26	100.00	6.75	100.00
2015	103,078	108.92	686,471.64	107.43	6.66	98.67
2016	116,399	123.00	839,046.40	131.30	7.21	106.81
2017	120,079	126.89	818,311.60	128.06	6.81	100.89
2018	128,656	135.95	899,742.45	140.80	6.99	103.56
2019	132,430	139.94	877,834.87	137.37	6.63	98.22
2020	124,333	131.38	934,700.27	146.27	7.52	111.41
2021	118,286	124.99	921,105.83	144.15	7.79	115.41
2022	120,594	127.43	959,776.75	150.19	7.96	117.93
2023	121,056	127.92	940,979.29	147.25	7.77	115.11
Average	117,955	-	851,699.14	-	7.22	-

Source: Author's calculation based on FAO data, www.fao.org/faostat/

Based on the calculations in Table 1, it can be seen that the average area under raspberry plantations in the world in the period 2014-2023 was 117,955 ha, the average volume of raspberry production was 851,699,14 t, and the average yield was 7.22 t/ha. The areas increased from year to year and reached a maximum in 2019 in the amount of 132.43 ha (about 40% more than in 2014), and then slightly decreased by the end of the period. The volume of production in the mentioned period increased and reached a maximum volume in 2022 (over 50% more than in 2014), and then slightly decreased by the end of the period. The average yield fluctuated by year during the period, where in 2015 and 2019 it decreased compared to the base year (1.5-2%) and reached a maximum in 2022 and amounted to 7.96

t/ha (about 18% more compared to the base year, 2014). The amounts and structure of average areas, production volumes and yields by continent and their share in the world, in the period 2014-2023 are calculated in Table 2.

Table 2. Average areas under plantations and structure, average volume of production and structure, and average yield of raspberries by continent and in the world, during the period 2014-2023

Continent /World	Area		Production volume		Average yield (t ha ⁻¹)
	ha	Share (%)	t	Share (%)	
Europe	91,396	77.48	556,743.60	65.37	6.09
America	19,781	16.77	247,689.28	29.08	12.52
Asia	3,305	2.80	14,971.24	1.76	4.53
Africa	3,136	2.66	31,609.50	3.71	10.08
Australia and N. Zealand	337	0.29	685,52	0.08	2.03
World (total)	117,955	100.00	851,699.14	100.00	7.22

Source: Author's calculation based on FAO data, www.fao.org/faostat/

Based on the calculations in Table 2, it is concluded that of the average total area under raspberry plantations in the world (117,955 ha) in the period 2014-2023 year, in Europe is located 77.48% (91,396 ha). Of the average total volume of production in the world (851,699.14 t), in Europe it was produced 65.37% (556,743.60 t). The average yield of raspberries in the world was 7.22 t/ha, where the highest average yield was achieved in America in the amount of 12.52 t/ha, while in Australia and New Zealand it was only 2.03 t/ha. According to data (FAO, 2025), in the structure of total raspberry production in the world in 2023 (940,979.29 t), the Russian Federation was in first place with a share of 23.31% (219,338.33 t), in second place was Mexico with a share of 20.24% (190,411.55 t), in third place was Serbia with a share of 10.49% (98,674.00 t), followed by Poland's share of 10.21% (96,100.00 t), USA's share of 6.66% (62,640.00 t), Morocco's share of 6.50% (61,181.00 t), Portugal's share of 3.79% (35,660.00 t), Spain's share of 3.51% (33,070.00 t) and other countries with a share of 15.29% (143,905.02 t). In the above countries, almost all production is carried out in the open field, and recently, production under cover - plastic tunnels or roof type - is more common.

Raspberry cultivation in Russia has a centuries-old tradition. Although Russian raspberry production is the largest in the world, the entire production is consumed on the domestic market - fresh and processed (Vapa-Tankosić et al., 2015). In Poland, the focus is on the sale of frozen raspberries, and exports are mainly directed to Germany, France and Belgium. In the USA, raspberry areas and production have had an almost continuous growth trend since the mid-1990s, which continues today. In Spain, raspberries have been grown for more than three decades, both in greenhouses and outdoors (Milošević et al., 2025). Chile is a traditionally important producer in the raspberry market, with significant investments in product quality through the establishment of traceability systems. Ukraine has become a rapidly growing exporter of frozen raspberries in recent years, with continued export growth and expansion into new markets such as the EU, the USA and Canada. In Portugal, it was historically the primary raspberry variety for jam production, while it is now the dominant variety for fresh consumption (Milošević et al., 2025). Mexico, as a relatively new player in the global raspberry market, is investing significantly in more modern plantations. The focus is on fresh raspberries, and production is mainly under

greenhouses and foils, as much as 80%, with high yields of 15-20 t/ha, hand-picking and packaging in the field itself. An analysis of the average total areas, production volumes and average yields in selected European countries and the share in Europe, during the period 2014-2023 is given in Table 3.

Table 3. Average areas and structure under plantations, average volume of production and structure and average yield of raspberries by selected European countries and in Europe, during the period 2014-2023

Country /Europe	Area		Production volume		Average yield (t ha ⁻¹)
	ha	Share (%)	t	Share (%)	
Poland	25,418	27.81	105,867	19.02	4.17
Russia	24,894	27.24	171,774	30.85	6.90
Serbia	19,876	21.75	107,289	19.27	5.40
Ukraine	4,960	5.43	33,664	6.04	6.79
Spain	2,243	2.45	37,720	6.78	16.82
United Kingdom	1,446	1.58	16,251	2.92	11.24
Portugal	1,170	1.28	22,274	4.00	19.04
Other countries	11,389	12.46	61,905	11.12	5.44
Europe (total):	91,396	100.00	556,744	100.00	6.09

Source: Author's calculation based on FAO data, www.fao.org/faostat/

According to the analysis (Table 3), the average total area under raspberry plantation in Europe during the period 2014-2023 year, amounted to 91,396 ha, where the dominant place belongs to Poland, a share of 27.81% (25,418 ha). Out of the average total volume of production in Europe (556,744 t), the largest volume was achieved in Russia, a share of 30.85% (171,774 t), and Serbia is in third place and in terms of area, a share of 21.75% (19,876 ha) and in terms of production, a share of 19.27% (107,289 t). Although Poland has the leading place in terms of areas under raspberry plantations in Europe, on the other hand, this country achieved the lowest average yield in Europe, in the amount of 4.7 t/ha during the analyzed period 2014-2023 year.

Raspberry production in Serbia - Serbia is one of the global leaders in the production of frozen raspberries, and almost all of its production is exported to the markets of developed countries. The average areas, average production volume, average yield by region and their share in Serbia, during the analyzed period 2014-2023, are calculated in Table 4.

Table 4. Average areas and structure, average volume of production and structure, and average yield by region and in Serbia, during the period 2014-2023

Region /Serbia	Area		Production volume		Average yield (t ha ⁻¹)
	ha	Share (%)	t	Share (%)	
Belgrade region	598.40	2.90	2,991.60	2.71	5.00
Vojvodina Region	1,002.00	4.86	5,254.80	4.75	5.24
The region of Šumadija and Western Serbia	16,894.00	81.87	94,123.30	85.16	5.57
Eastern Region and Southern Serbia	2,140.40	10.37	8,162.30	7.38	3.81
Serbia (total):	20,634.80	100.00	10,532.00	100.00	5.36

Source: Author's calculation based on SORS data, Statistical yearbooks, 2014-2023, www.stat.gov.rs

Raspberry production in Serbia is territorially concentrated in: Western Serbia - Arilje, Požega, Užice, and Ljubovija), Northwestern Serbia - Valjevo, Šabac, Osečina) and Southwestern Serbia - Brus, Aleksandrovac and Kuršumlja (Veljković et al., 2025). According to the calculation in Table 4, looking at the average by region for the period 2014-2023, the largest areas under raspberry plantations are located in the Shumadija and Western Serbia Region, with a share of 81.87% (16,894 ha) in the total average areas under raspberry plantations in Serbia (20,634.80 ha). Also, the largest average total volume of raspberry production is in the same region, with a share of 85.16% (94,123.30 t). The average raspberry yield in Serbia during the analyzed period 2014-2023 was 5.36 t/ha, with the highest average yield in the Shumadiya and Western Serbia Region at 5.57 t/ha and the lowest in the Eastern and Southern Serbia Region at 3.81 t/ha.

Over 80,000 holding s in Serbia produce raspberries, the dominant variety is Willamett with a 95% share in total production, and it is mainly intended for freezing. Over 95% of raspberry production in Serbia is purchased by a large number of cold stores. Over 500 cold stores are involved in the purchase process, starting from micro-ones, with a few dozen tons of capacity, which serve as exclusive intermediaries, to the largest ones, with a capacity of several thousand tons, which produce and market final products (CCIS, 2025). In the period 2014-2023, average annual producer prices fluctuated by year from a low of 0.82 euro per kilogram in 2018 to a high of 4.12 euro per kilogram in 2022. The average selling price of raspberries at the Kvantaška market in Belgrade in the period 2014-2023 fluctuated by year, from a low of 1.66 euro per kilogram in 2018 to a high of 5.83 euro per kilogram in 2022. At green markets, selling prices of raspberries also varied by year, from a low of 1.91 euro per kilogram in 2018 to a high of 6.03 euro per kilogram in 2022 (<https://www.stips.minpolj.gov.rs/>).

Indicators of Profitability of Raspberry Production

Production, financial and market conditions, input and output price ratios, and other factors greatly influence the profitability of investing in this production (Galić et al., 2014; Bodiroga and Sredojević, 2017). According to data collected through interviews with producers in practice on the holding s of Western Serbia, as well as professional standards of raspberry production technology for the Willamett variety according to the vertical spalir system, with a planting distance of 2.50 x 0.25 m, the investment in raising 1 ha of plantations of this fruit species was determined (Table 5). The planned number of seedlings is 16.000, the planting period lasts two years, and the "small crop" of raspberries arrives in the second year after planting. Investments are determined by an interest rate of 8%.

Table 5. Total investments in establishing and growing 1 ha of raspberry plantations (Area: 1 ha; Cultivation system: spalir; 16.000 seedlings/ha)

Economic parameters	Years of establishment and raising of plantations (m)			Total (€)
	0	1	2	
Costs of materials	4,000.00	680.00	820.00	5,500.00
Labor work	340.00	330.00	260.00	930.00
Machine operation	250.00	240.00	190.00	680.00
Investing in an irrigation system	-	3,300.00	-	3,300.00
Design, supervision and control	220.00	200.00	180.00	600.00

Construction of auxiliary facilities, roads, etc.	150.00	150.00	200.00	500.00
Total investments from 1 to 7	4,960.00	4,900.00	1,650.00	11,510.00
The value of a “small” raspberry yield	-	-	530.00	530.00
Adjusted total investments (7-8)	4,960.00	4,900.00	1,120.00	10,980.00
Correction factor (1,08 ^m)	1.1664	1.0800	1.0000	-
Total investments at the beginning of the plantation exploitation period	5,785.00	5,292.00	1,120.00	12,197.00

Source: Author's calculation based on average amounts in the practice of raising raspberry plantations on family holdings in Western Serbia

With the calculative procedure in Table 5, investment investments increased by the appropriate amount of interest, at the end of the raspberry planting period (i.e. at the end of the second year), were determined in the amount of 12,197.00 euro per hectare. According to research results, the application of irrigation to smaller areas gave positive results in the form of high and uniform yields of quality raspberry fruits (Gajić et al., 2013). For the purposes of this research, based on data from the practice of raspberry production in Western Serbia, a calculation of individual and total costs of raspberry production per unit area was compiled. Based on the technological map, that is, the list of work processes (which was omitted due to limited space), from the spring work in the raspberry orchard, ending with the raspberry harvest, the amounts and structure of the total costs of raspberry production on an area of 1 ha were determined (Table 6).

Table 6. Total costs of raspberry production on a family holding on an area of 1 ha

Cost elements	Amount (€ ha ⁻¹)	Share (%)
Costs of materials (fertilizer, pesticides, water. etc.)	2,370.00	22.00
Machine operation	2,630.00	24.00
Labor work (own and hired)	4,870.00	45.00
Other costs (amortization, contractual obligations, etc.)	930.00	9.00
Total costs (1+2+3+4):	10,800.00	100.00

Source: Author's calculation based on raspberry production data on family holdings in W. Serbia

The total costs, which include the costs of: materials, machine operation, labor work engaged in the work in the raspberry plant and other costs, during regular raspberry production, amount 10,800 euro per hectare (Table 6). Given that in this area, raspberries are still harvested by hand, in the structure of total costs, labor costs have the largest share (45%). Based on the average yield of 5.3 t achieved in practice on the analyzed holding s in the Arilje area, as well as the average purchase price of raspberries of 4.0 euro per kilogram, the production value for one production cycle was determined. Of the economic indicators, the following were determined: financial result, cost price of one kilogram of raspberry, economy coefficient, accumulative rate and investment return period (Table 7).

Table 7. Economic indicators of planting and production of raspberries on a family holding

Economic indicators	Amount
I Total investments in raising raspberry plantations	12,197.00 €
II Economic indicators of annual raspberry production	
Production value (5,300 kg * 4.0 € kg ⁻¹)	21,200.00 €
Total costs	10,800.00 €
Financial result: profit/loss (1-2)	10,400.00 €
Cost price of 1kg of raspberries (2/5,300 kg)	2.04 €
Efficiency coefficient (1/2)	1.96
Accumulation rate (3/I)	85%
Pay back period (I/3)	1.17 years

Source: Author's calculation based on raspberry production data on family holdings in W. Serbia

Using the calculative procedure in Table 7, the production value was determined in the amount of 21,200 euro per hectare. The difference between the production value and total costs gives a positive financial result (profit) in the amount of 10,400 euro per hectare. The cost of raspberries is 2.04 euro per kilogram and is much lower compared to the selling (repurchase) price of 4.0 euro per kilogram, which is favorable for raspberry producers. The efficiency coefficient is 1.96 and is far above the minimum amount of 1. The accumulation rate shows that for every 100 euro of invested capital, about 85 euro is achieved for accumulation. The return time of invested capital in establishing and growing raspberry is 1.17 years, i.e. the invested capital can be recovered in the second year of exploitation of raspberry plantations. Based on the established indicators and assessments based on appropriate criteria, it can be concluded that raspberry production is economically justified, highly profitable for producers, and provides economic security and sustainability for families for whom it is the main and only source of income. According to the latest data, there are around 500 cold storage facilities in Serbia with a capacity of 600,000 t that are engaged in fruit freezing (CCIS, 2025). During the season, these facilities are regularly inspected, and the Ministry of Internal and Foreign Trade is solely responsible for illegal purchase points, which represent one of the biggest problems during the raspberry harvesting and purchase season.

Foreign Trade Balance of Serbian Raspberries

The sale of raspberries on the domestic market is negligible. Almost all frozen raspberries are exported from Serbia. In 2024, 79,582 t of raspberries were exported from Serbia, worth 247.3 million euro (SORS, 2025). Raspberries were mainly exported frozen (almost 99%). The largest quantities of raspberries were exported to the European Union countries: Germany, France, Belgium, the Netherlands, Austria and Sweden. Of the other countries, raspberries were exported to the USA, Great Britain, Switzerland, Canada, Argentina and others. Germany and France are the largest buyers of Serbian raspberries and exports to these two countries account for almost 50% of total raspberry exports. In the value of total fruit exports in 2024, which amounted to 746.5 million euro, raspberries accounted for 33.1%. In 2024, into Serbia were imported 2.319 t of raspberries, with an import value of 6.3 million euro (SORS, 2025). The largest amount of raspberries was imported from Bosnia and Herzegovina, over 50% of the total imported raspberries, in the amount of 1.385 t and a value of 3.5 million euro, and significantly less from other countries. The average

amounts of exports, imports and foreign trade balance of raspberries of Serbia for the period 2014-2023 are determined in Table 8.

Table 8. Average amounts of export and import of raspberries to the European Union and the world and the foreign trade balance of raspberries in Serbia, during the period 2014-2023

Indicators	Export		
	World	EU	EU share in the world (%)
Fresh raspberries (t)	3,513.3	3,489.3	99.32
Frozen raspberries, sugar-free (t)	90,993.2	76,344.4	83.90
Fresh raspberries (in 000 USD)	6,914.2	6,850.0	99.07
Frozen raspberries, sugar-free (in 000 USD)	284,089.1	231,336.4	81.43
Total (in 000 USD)	291,003.3	238,186.4	81.85
Import			
Fresh raspberries (t)	103.7	88.2	85.05
Frozen raspberries, sugar-free (t)	6,801.3	1,054.9	15.51
Fresh raspberries (in 000 USD)	370.4	272.9	73.68
Frozen raspberries, sugar-free (in 000 USD)	17,776.4	3,136.6	17.65
Total (in 000 USD)	18,146.8	3,409.5	18.79
Foreign trade balance			
Fresh raspberries (t)	3,409.6	3,401.1	99.75
Frozen raspberries, sugar-free (t)	84,188.9	75,289.5	89.43
Fresh raspberries (in 000 USD)	6,543.8	6,577.1	= 100.00
Frozen raspberries, sugar-free (in 000 USD)	266,312.7	228,199.8	85.69
Total (in 000 USD)	272,856.5	234,776.9	86.04

Source: Author's calculation based on SORS data, <https://data.stat.gov.rs/>

Based on the calculations in Table 8, during the period 2014-2023, the average export of frozen raspberries from Serbia amounted to 90,993.2 t and 3,513.3 t of fresh raspberries, and the average value of total exported raspberries amounted to over 291 million US dollars. Of this amount, over 99% of raspberries were exported to the EU, and about 1% to other countries in the world. The average import of frozen raspberries to Serbia in the same period amounted to 6,801.3 t and 103.7 t of fresh raspberries, and the average value of total imported raspberries amounted to 18.1 million US dollars. Therefore, during the analyzed period, Serbia's raspberry exports and imports achieved a positive foreign trade balance in the amount of 84,188.9 t of frozen raspberries and 3,409.6 t of fresh raspberries, with a total value of 272.8 million US dollars. Improving the frozen raspberry value chain requires strengthening the market position, as well as introducing innovative value-adding phases, meeting the necessary standards, but also a joint approach, which would to some extent solve the problem of low bargaining power (Sredojević et al., 2013; Milić et al., 2017). Value addition is primarily achieved through new types of processing, such as freeze-drying, delivery of raspberries in "retail-ready" packaging, etc. A certain number of cold storage exporters have managed to bypass intermediaries and add about 20% to the selling price through packaging in smaller packages. However, the share of such exports in total frozen raspberry exports is still low and does not exceed 10 to 15% (CCIS, 2025). For higher value-added products, key activities are introducing new phases to finalize the

product, mastering finishing and processing techniques, dissemination of market information, promotion and branding of final products (Sredojević et al., 2013). The export of raspberries and other berries from Serbia generates a significant foreign exchange inflow, and therefore efforts should be made to preserve partnership relations with subcontractors and buyers abroad. Continuity and constant work on improving production and marketing are needed, in which all actors in the Serbian raspberry value chain should participate.

CONCLUSION

Raspberry is a specific fruit species that stands out from other berries in terms of its economic importance and market value in Serbia. The total area under raspberry plantations in 2024 in Serbia was 18,625 ha, the production volume was 94,026 t, and the average raspberry yield was 5 t/ha. The most common variety in raspberry plantations is Willamette, which is intended for freezing, with over 90% of the share. In 2024 from Serbia were exported 79.582 t of raspberries in worth 247.3 million euro. Of the total exported quantities of raspberries, over 98% were exported frozen. During the period 2014-2023 the average value of total exported raspberries from Serbia was over 291 million US dollars. During the same period, Serbia's raspberry exports and imports achieved a positive foreign trade balance worth a total of 272.8 million US dollars. Today, small quantities of fresh raspberries are exported from Serbia. They are mainly sold on the domestic market, 2-4% of total production.

However, the transition to the production and marketing of fresh raspberries for consumption requires significant investments, primarily the introduction of a new assortment, to obtain larger fruits more suitable for consumption and a longer shelf life, then more intensive irrigation, as well as production in greenhouses in order to extend the season and improve yield and quality. Although it is one of the world's largest raspberry producers, Serbia hardly produces or exports jams, juices and other raspberry products. The demand for organic raspberries is still higher than the supply, and the prices achieved are significantly higher than the frozen segment. A series of irregularities accompany the harvesting and purchase of raspberries in Serbia, and the biggest problem is still unregistered purchase points.

According to established indicators and assessments based on appropriate criteria, raspberry production in the current conditions in Serbia is economically justified, profitable and sustainable for producers, providing economic stability and security for families for whom it is the main and only source of income. Stronger control in the value chain, with clear traceability by stage, provides the opportunity for better quality and compliance with EU standards. High quality protected geographical origin, such as Arilje raspberries form the basis for strengthening the competitive position in the international market. In order to further improve and preserve the existing competitive position, the Serbian raspberry sector should focus on higher levels of added value and market diversification. The future and sustainability of family holding s focused on raspberry production, as well as the Serbian raspberry sector, lies in further strengthening existing and developing new value chains.

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APITOURISM IN THE CONTEXT OF THE ECONOMIC DIMENSION AND OPPORTUNITIES FOR SUSTAINABLE AGRIBUSINESS

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Abstract: Apitourism represents a specific form of tourism that can be classified as an innovative segment of rural, that is, agritourism. Its accelerated development on the tourism market has emerged over the past decade through the integration of beekeeping with tourism services, thereby creating additional economic value for agricultural holdings. In this context, this paper analyzes apitourism from the perspective of its economic dimension and the opportunities it offers for sustainable agribusiness, with particular emphasis on income diversification, the preservation of rural communities, and the promotion of the sustainable use of natural resources. By considering not only economic but also social and environmental aspects, the paper highlights the significant potential of apitourism to contribute to local development, stimulate employment-especially among economically vulnerable groups in rural areas-and promote environmentally friendly practices, including the enhancement of the competitiveness of agritourism products and the long-term sustainability of agribusiness.

Keywords: Apitourism, Opportunities, Sustainable agribusiness, Economics

INTRODUCTION

Green transformation, along with numerous innovations, represents both the contemporary environment and the future of agribusiness. In this context, one of the innovative forms of rural tourism, namely agrotourism, is the increasingly popular apitourism. Apitourism, or beekeeping tourism, may represent either a primary or a supplementary activity of an agricultural holding, enabling additional income generation and thereby emphasizing the economic dimension as well as the diverse opportunities agribusiness possesses within the tourism market. In recent years-particularly following the 2020 pandemic period-a significant increase has been observed in public interest in the consumption of healthy and organic food, as well as in concern for health preservation and prevention.

The pandemic influenced the reassessment of everyday habits, attitudes toward physical and mental health, and the overall improvement of quality of life, while also intensifying the need to strengthen immunity and focus on combating stress as a global contemporary challenge. Consequently, health has become one of the key priorities of modern society, not only in the context of treatment but also through preventive and holistic approaches.

Digital media, along with the accessibility and rapid dissemination of information, have further contributed to strengthening individual responsibility for maintaining personal well-being. This has been largely driven by global health challenges and increased awareness of the importance of disease prevention. These changes are also reflected in the development of new market trends in tourism, including the growing interest in health, rural, and agrotourism, as well as in functional and healthy food and sustainable forms of agribusiness. As a result, health is increasingly positioned as an important factor of social and economic development. In this regard, apitourism stands out as one of the future sustainable models of agribusiness that integrates economic, environmental, and social aspects of development, in line with contemporary health trends and changes in the global tourism market. By connecting beekeeping, tourism, and health-educational content, apitourism has emerged as a significant segment of agribusiness.

Through the offer of natural bee products, apitherapy services, educational workshops, and stays in predominantly preserved and unspoiled natural environments, apitourism meets modern tourist demands and their need for a healthy lifestyle during travel. At the same time, apitourism enables income diversification for agricultural holdings, encourages biodiversity conservation, influences the touristic development of rural households, and contributes to the creation of supplementary tourism products and content for various tourist segments, which altogether positively affects the development of rural areas.

CONTRIBUTION OF TOURISM TO RURAL DEVELOPMENT

Tourism plays a significant role in the development of rural areas, as it represents one of the key factors for the economic empowerment of local communities and the improvement of the quality of life of the indigenous population. The development of rural tourism, particularly agrotourism, enables the diversification of economic activities in rural areas, reduces dependence on traditional agriculture, and creates new opportunities for the agriculturally active population through the generation of additional income sources for rural households, including accommodation, catering, recreational, and educational services. Through the economic strengthening of local communities and the improvement of living standards in rural areas, tourism can be positioned as one of the main drivers of rural development. Specifically, the development of rural tourism creates additional income opportunities for agricultural holdings through the provision of accommodation, food services, recreational activities, participation in everyday farm work, as well as the direct sale of local agricultural products to consumers. In this way, economic dependence on agricultural production alone is reduced, while resilience to market and climate changes is increased. In addition to economic benefits, tourism also has a significant social and cultural contribution to rural development. The creation of new jobs contributes to the reduction of unemployment and poverty, as well as to limiting rural-to-urban migration, particularly among younger generations, thereby creating conditions for the survival and economic revitalization of rural areas. At the same time, tourism encourages the preservation and valorization of cultural heritage, traditions, customs, folklore, handicrafts, traditional crafts, and local identity, which become an important segment of the tourism offer in rural destinations. The development of tourism in rural areas also plays an important role in environmental protection and the sustainable use of natural resources. The promotion of environmentally responsible tourism contributes to biodiversity conservation and the preservation of natural assets, while simultaneously raising awareness among local

residents and tourists about the importance of sustainable development. In this way, tourism contributes to integrated rural development by linking economic, social, and environmental dimensions in support of the long-term sustainability of rural areas. Numerous benefits of tourism development in the context of sustainable rural development have been highlighted by various tourism theorists, who have identified some of the most significant among them.

Tourism has been a key strategy for revitalizing rural areas facing depopulation, land abandonment, and economic decline (Izquierdo-Gascón and Rubio-Gil, 2023). The development of wine and food tourism can reinforce local economies by attracting visitors and new inhabitants to small and picturesque rural areas (Tomay and Tuboly, 2023). Using rural tourism as a revitalization strategy is beneficial to nonurban communities in terms of their economic, socio-cultural, environmental, and leisure and educational development. The contribution from the economic perspective is particularly important (Liu et al., 2023). Tourism can play an important role in diversifying the rural economy and its expanding in rural areas contributes to the sustainability of the population and the economy of these areas and provides the basis for achieving sustainable rural development (Nooripoor et al., 2021).

Tourism, especially rural tourism, is one of the factors of sustainable economic development in the world and one of the characteristics of tourism development in a country. According to the economic approach to tourism development, tourism is now known as an industry because of the inclusion of material and financial income, so it can be used as a means to achieve economic development (Mohammadi et al., 2022).

Rural tourism is a vital means of rural development. There is a great deal of interdependence and complementarity between the two. Rural tourism offers an alternative attraction of rurality as a diversification and regenerative strategy to bring about socio-economic development with minimal adversity (Singhania et al., 2022).

Both the expansion of tourism land use and the mass removal of settlements have played a role in the decline of traditional villages. Several instances demonstrate that profit-driven tourism development has intensified the transformation of traditional villages into mere museums, rather than promoting sustainable development. Furthermore, the heavy dependence on a solitary tourism-based source of income renders traditional communities exceedingly susceptible to unforeseen circumstances, such as the outbreak of the Covid-19 pandemic. Preserving traditional livelihoods and diversifying livelihoods enhances the ability of traditional villages to maintain their rural character and sense of place, while also strengthening the authenticity of rural tourism (Yanan et al., 2024).

CONCEPT AND DEVELOPMENT OF APITOURISM

In recent years, apitourism or beekeeping tourism has become a modern trend in the tourism market, as well as a development opportunity in the field of agro-business. Originating less than a decade ago in the Republic of Slovenia, after the Government of this country adopted a strategy for integrating beekeeping and tourism, it can be classified as selective, that is, specific or special forms of tourism. Due to the health benefits in the field of apitherapy, it is often associated with health tourism, while its characteristics are inevitably connected to rural tourism (Stanić Jovanović, 2025).

Apitourism is a form of tourism that deals with the culture and traditions of rural communities and can be considered one of the most sustainable methods of development and tourism (Fathi et al., 2022). Apitourism is becoming more popular internationally and internally. It is a niche that if used properly, can be a powerful catalyst for beekeeping in the country (Grigorova et al., 2016). Apitourism combines sustainable beekeeping, niche, historical heritage, and health tourism as an intersection between tradition, alternative medicine, and the sustainable income-generating activity of the beekeeper (Beigi, 2018; Tišler and Šuligoj, 2020; Wos, 2014). Apitourism is a key segment of the green economy, as it significantly promotes the economic efficiency of beekeeping and follows the principles of the strategy for the development of sustainable tourism (<https://sca.kis.si/en/>).

Apitourism is an innovative form of agritourism where tourists learn about the life and work of bees, bee products, and everything related to beekeeping. It also offers special services such as inhaling air from the beehive, honey massages, honey baths, cosmetics based on bee products, and more. In short, apitourism focuses on raising awareness about the importance of bees in the ecosystem, beekeeping, and educating visitors about the life and work of bees, the functioning of the bee community, and the production of bee products. Currently, apitourism is becoming increasingly popular due to the growing interest in apitherapy and wellness, which includes bee products (Škaro, 2021).

Apitourism is not yet fully utilized and has significant potential for growth and development. It requires a great deal of effort and knowledge, as well as attracting a large number of people who will recognize the importance of apitourism and the healing properties of bee products. Apitourism holds much more potential. Through apitourism, visitors can relax, unwind, have fun, and even learn something new. First and foremost, visitors can participate in a small workshop organized by the local tourism community. After the workshop, they learn how honey is extracted, and at the end, they reap the fruits of their labor, enjoying them through food, massage, wellness treatments, and similar experiences (Bakavić, 2020).

Apitourism was born in Slovenia in 2016, after the Slovenian government, at the suggestion of the beekeeping association, became the first to adopt a strategy for integrating beekeeping and tourism. Slovenia is the world's leading destination for beekeeping, or apitourism, with over 10,000 beekeeping farms and more than 17,000 beekeeping colonies and is one of the first countries to offer certified apitourism services. The Slovenian Tourist Organization and the Slovenian Beekeeping Association have jointly developed a series of initiatives for a sustainable approach to apitourism. They provided support to travel agencies in creating packages that offer tourists interesting combinations of rich eco-content, such as wellness vacations combined with local honey tastings. This trend spread globally, and api-centers began to develop in many countries, from Croatia, Bosnia and Herzegovina, and Serbia to Greece and the United States. Apitourism experienced a boom in Serbia and the region after the outbreak of the COVID-19 pandemic, when people began to turn to nature and a healthier lifestyle. Following the proposal of the Slovenian Beekeeping Association, the United Nations General Assembly declared 20 May 2017, as World Bee Day (Jovanović et al., 2023).



Figure 1. Apitherapy Chamber, Temerin, Serbia
Source: www.utnv.org/api-komora-temerin/

Slovenia was the first in the world to develop apitourism - an innovative tourist product that is a combination of tourism and beekeeping. It is a unique travel experience and a form of sustainable and responsible tourism linked to the tradition of beekeeping. Currently, there are already 45 certified providers of apitourism services in Slovenia. We are the only ones in the world to have beekeeping tourist guides. Slovenia took the initiative in 2014 to make 20 May World Bee Day. As part of the initiative, Ministry of Agriculture, Forestry and Food representatives travelled around the world with the Bee World pavilion, actively promoting and raising awareness about the initiative and other support projects. In doing so, they held numerous bilateral meetings with representatives of other countries and international organizations and organized professional events. The response of the Slovenian and international public was positive, the initiative was supported by top Slovenian politicians, the world beekeeping organization Apimondia, the United Nations Food and Agriculture Organization (FAO), the European Union and many other organizations. After more than three years of efforts, a resolution to declare World Bee Day was adopted on 17 November 2017 by the UN Economic and Financial Committee. The resolution was then unanimously approved by the UN General Assembly in New York on 20 December 2017, declaring 20 May as World Bee Day. It was supported by all UN countries, with 115 countries co-sponsoring it, including some of the largest countries, such as the United States, Canada, China, Russia, India, Brazil, Argentina, Australia and all European Union countries (<https://sca.kis.si/en>).

OPPORTUNITIES FOR THE DEVELOPMENT OF APITOURISM IN THE CONTEXT OF SUSTAINABLE AGRIBUSINESS

Tourism has been a key strategy for revitalizing rural areas facing depopulation, land abandonment, and economic decline (Uldemolins et al., 2025). A significant role in improving rural tourism and agribusiness, with considerable development effects, is played by apitourism or beekeeping tourism, which is becoming an increasingly popular trend in the tourism market (Stanić Jovanović, 2025). Experiencing apitourism activities creates a more positive opinion in tourists. It is understood that apitourism guides are knowledgeable about bee biology, fun, hospitable, passionate about their job and proficient in foreign languages. Visitors described the guides' expertise in this field with expressions such as "bee apiologist", "walking encyclopedia", "bee doctor", "bottomless wealth" and "bee wizard" (Dönmez, 2024).

Beekeeping encourages the socio-economic revitalization of rural areas, diversifies agricultural production, and offers new opportunities for both beekeepers and tourists (Topal et al., 2021). Hosts, through rural tourism services, have the opportunity to sell surplus agricultural products, often at significantly higher prices than market rates. The development of rural tourism is gaining increasing importance due to its potential contribution to the social and economic renewal of rural areas and the revitalization of villages. This form of tourism is based on sustainability principles, offering tourists elements of rural life, nature, and traditional hospitality (Stanić Jovanović et al., 2025).



Figure 2. Interior View of the Api Chamber
Source: www.turizambackipetrovac.rs

The increasing interest in beekeeping has led to one of the most sustainable forms of travel. The knowledge of this millenary art and its determining role in the preservation of biodiversity leads to current diverse educational experiences such as: attending the different talks and workshops offered globally, becoming a beekeeper for a day, seeing the live honey collection, acquiring knowledge of local gastronomy, supporting artisan crafts, and taking part in flora and honey routes. These activities are part of Apitourism, a growing concept that thanks to successful and long-lasting examples, such as the case of Slovenia, encourages local and proximity tourism (Izquierdo-Gascón and Rubio-Gil, 2023).

Apitourism is a form of tourism associated with beekeeping as a traditional profession and bee products in ecological, nutritional, and medical aspects. Activities related to beekeeping tourism include visits to apiaries, open-air museums, and bee museums where tourists can learn about the local characteristics of apiculture. Although apitourism in Bosnia and Herzegovina is most often identified with api chambers, i.e., the application of air from beehives to treat various diseases and other states, most often respiratory problems, this term has a much broader meaning. Apitourism as a branch of health tourism has a much wider potential than the use of api chambers. At the same time, this tourist branch can be a part of sustainable rural tourism (Sinanović and Santrač, 2022).

Providers of apitourism do not only sell bee products and crops, but their own story. Through their story of specialization and niche tourism, they have the opportunity to create added value to their products. By offering apitourism as competitive advantage, they create experiences. Customers and visitors not only buy their products, but they hear the story of bees, why they are important to humanity, why bee products have so much positive effects on humans, especially through personal presentation in an authentic environment they see, experience and learn about the importance of bees for the existence of humanity. Providers

of apitourism differ from each other in terms of their offer. It is important that the provider specializes and develops a complete story about its offer. The offer of apitourism is interesting for almost all target groups: children, teenagers, adults, elderly, families, students, businessmen, associations, domestic and foreign visitors. The additional offer opens up new markets and opportunities for the provider to increase sales as well as an additional source of income from tourism (Korošec, 2022).

CONCLUSION

Following contemporary trends in the global tourism market, numerous changes in tourist demand can be observed. The modern tourist is generally educated and experienced, often knowing precisely what they expect from their travel experience. In this context, the foremost needs include active leisure activities, stays in preserved natural environments (except in urban tourism, although even there is a growing tendency to organize excursions in nearby natural areas), participation in immersive and interactive activities, as well as the availability of healthy, typically organic food and handcrafted local products that do not pose health risks. Tourism providers are making dedicated efforts to respond to these evolving demands and preferences. The significant popularity of apitourism serves as a prime example of good practice in addressing these contemporary tourist expectations.

Apitourism connects beekeeping as a primary activity with tourism and can be classified as a special or selective form of tourism. This relatively young form of tourism has been actively developing for nearly a decade and, due to its significance in terms of economic dimensions and opportunities for agribusiness, represents an essential development potential for all rural destinations within the tourism market. Although it is most commonly associated with api chambers and their health benefits-particularly for respiratory conditions and the prevention of various psycho-physical disorders, including widespread stress and so-called “managerial disease”- apitourism can encompass a much broader range of tourist products and services. In addition to the sale of local bee products, tourists are also interested in honey-based foods and beverages (e.g., honey cakes, mead, etc.), alongside the ever-present accommodation services in rural households. Furthermore, specific opportunities for sustainable agribusiness include: organizing beekeeping-related events and festivals; designing creative supplementary content for visitors (especially families with children, through animation and games); as well as storytelling and educational activities (offering beekeeping experiences through immersive stays on apiary farms and educating visitors about honey and beekeeping). Networking with the local tourism offer and designing mini-tours in the form of half-day trips or excursions also present additional opportunities. In this regard, both natural and anthropogenic tourist resources in the immediate vicinity of agricultural and beekeeping holdings may present a challenge for hosts, as tourists often seek to familiarize themselves with rural tourism destinations, local customs, traditions, handicrafts, legends, and other forms of intangible cultural heritage.

From the foregoing, the significant potential of beekeeping tourism, or apitourism, can be clearly observed, particularly in terms of the opportunities it offers local hosts for sustainable agribusiness. In this way, the economic dimension of apitourism is highlighted, as it can contribute to the sustainability of rural and agrotourism through increased income generated by the sale of apitourism-related products. However, apitourism requires

knowledge across various fields, including economics, marketing, management, consumer psychology, tourism studies, beekeeping, and even medicine (such as providing first aid in cases of anaphylactic shock). Therefore, the education and training of hosts in apitourism is a priority, alongside the quality of the tourism services provided and the standard of apitourism products, which are essential for attracting both domestic and international visitors and for securing a competitive position in the tourism market.

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APPLICATION OF GIS AND REMOTE SENSING FOR AGRICULTURAL LAND SUITABILITY ASSESSMENT: A CASE STUDY IN SERBIA

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Abstract: This study presents a GIS-based multi-criteria analysis for agricultural land suitability assessment in the Mačva District, Serbia. Satellite imagery from Sentinel-2 and spatial datasets including soil type, slope, precipitation, and land use were integrated using the Analytical Hierarchy Process method. Results indicate that 42.3% of the study area is highly suitable for crop production, while 28.7% require improvement measures. The developed methodology provides a framework for sustainable agricultural land use planning.

Keywords: GIS, Remote sensing, Land suitability, Sustainable agriculture, Multi-criteria analysis

INTRODUCTION

Sustainable agricultural development requires optimal utilization of land resources based on their inherent capabilities and limitations. Geographic Information Systems (GIS) and remote sensing technologies have become essential tools for agricultural land evaluation, enabling the integration of multiple spatial datasets and supporting evidence-based decision-making processes (FAO, 2007; Akinci et al., 2013). The growing pressure on agricultural land from urbanization, climate change, and population growth necessitates comprehensive land evaluation approaches that can guide sustainable land use planning.

Serbia, as a country with significant agricultural potential, faces challenges related to land degradation, climate change impacts, and suboptimal land use practices. Agriculture contributes approximately 7% to the national GDP and employs about 15% of the workforce, making it a crucial sector for economic development (Statistical Office of the Republic of Serbia, 2023). The Mačva District, located in western Serbia, represents one of the most productive agricultural regions, yet comprehensive spatial assessments of land suitability remain limited. Traditional land evaluation methods often fail to account for the complex interactions between environmental factors that determine agricultural productivity (Feizizadeh and Blaschke, 2013).

Multi-criteria decision analysis (MCDA) combined with GIS provides a robust framework for integrating diverse spatial datasets and expert knowledge into land suitability models. The Analytical Hierarchy Process (AHP), developed by Saaty (1980), has been widely applied in agricultural land evaluation due to its ability to handle both quantitative and

qualitative criteria while maintaining methodological transparency (Kazemi and Akinci, 2018). The AHP method allows decision-makers to decompose complex problems into hierarchical structures and derive priority weights through pairwise comparisons.

Remote sensing data, particularly from the Sentinel-2 satellite constellation operated by the European Space Agency, offers high spatial and temporal resolution imagery suitable for monitoring vegetation health and land cover dynamics. The Normalized Difference Vegetation Index (NDVI) derived from satellite imagery serves as a reliable indicator of crop vigor and agricultural land productivity (Rouse et al., 1974). The free availability of Sentinel-2 data since 2015 has significantly enhanced the accessibility of remote sensing applications for agricultural monitoring.

The objective of this study is to develop and apply a GIS-based multi-criteria methodology for agricultural land suitability assessment in the Mačva District, integrating remote sensing data with environmental variables to support sustainable land use planning and agricultural policy development. The specific aims include: (1) identifying and weighing relevant criteria for agricultural land evaluation, (2) mapping land suitability classes across the study area, and (3) comparing the results with current land use patterns to identify optimization opportunities.

MATERIAL AND METHODS

Study Area

The Mačva District is located in western Serbia, between 44°30' and 45°00' N latitude and 19°00' and 19°45' E longitude (Figure 1).

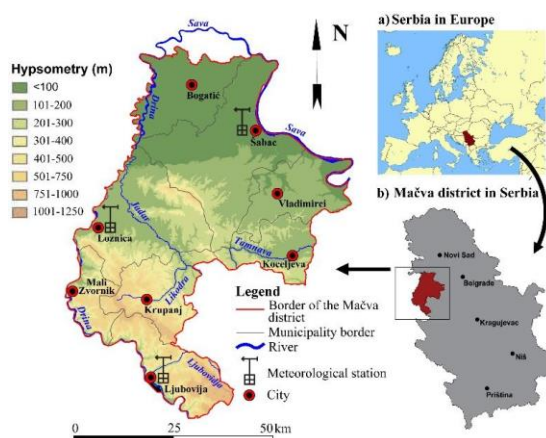


Figure 1. Location of the Mačva District study area in western Serbia, with hypsometry and administrative boundaries. Source: Adapted from Milentijević et al. (2020)

The district covers approximately 3.270 km² and includes eight municipalities: Šabac, Bogatić, Vladimirci, Koceljeva, Krupanj, Ljubovija, Loznica, and Mali Zvornik. The terrain is predominantly flat to gently undulating, with elevations ranging from 80 m in the alluvial plains to 600 m in the hilly southern portions. The climate is temperate continental, with mean annual temperature of 11.2°C and precipitation of 700-850 mm (Republic

Hydrometeorological Service of Serbia, 2023). The region is characterized by fertile alluvial soils along the Sava River and its tributaries, supporting intensive crop production including maize, wheat, sugar beet, and various vegetables.

Data Sources

The following spatial datasets were utilized in this study:

Sentinel-2 imagery: Multispectral imagery (10 m resolution) acquired during the growing season (May-August 2022) was obtained from the Copernicus Open Access Hub (<https://scihub.copernicus.eu/>). A total of 12 cloud-free images were selected for NDVI calculation and land cover classification. The Sentinel-2 Level-2A products with atmospheric correction were used to ensure radiometric consistency (ESA, 2022).

Digital Elevation Model (DEM): A DEM with 25 m spatial resolution was obtained from the Copernicus Land Monitoring Service EU-DEM v1.1 (<https://land.copernicus.eu/imagery-in-situ/eu-dem>). Slope and aspect layers were derived from the DEM using standard GIS algorithms implemented in QGIS (EEA, 2016).

Soil data: Soil type, texture, and depth data were digitized from the Basic Pedological Map of Yugoslavia (1:50.000 scale) produced by the Institute of Soil Science, Belgrade (Tanasijević et al., 1964). The original soil classification follows the Classification of Yugoslav Soils (Škorić et al., 1985), which remains the official system in Serbia (Pavlović et al., 2017). For international comparability, soil classes were correlated to the World Reference Base for Soil Resources (IUSS Working Group WRB, 2015) following established correlation approaches for Serbian soils (Radmanović et al., 2020).

Climate data: Mean annual precipitation and temperature data were interpolated from 15 meteorological station records obtained from the Republic Hydrometeorological Service of Serbia (RHMSS) for the period 2014-2022. Data was accessed through the RHMSS official database (www.hidmet.gov.rs/). Spatial interpolation was performed using the Inverse Distance Weighting (IDW) method following the approach described by Gocić and Trajković (2013).

Land cover classification: The Random Forest algorithm was applied for supervised classification with an overall accuracy of 87.3%, which is consistent with reported accuracies for Random Forest classification of Sentinel-2 imagery in Central-Eastern European landscapes, typically ranging from 82 to 89% (Pflugmacher et al., 2019; Immitzer et al., 2016).

Hydrological data: River networks and water bodies were obtained from the OpenStreetMap database (www.openstreetmap.org/) and verified using Sentinel-2 imagery. Distance to water sources was calculated using Euclidean distance analysis.

Methodology

The land suitability assessment followed the FAO Framework for Land Evaluation (FAO, 1976) adapted for local conditions, as recommended by Rossiter (1996). Five criteria were selected based on literature review and expert consultation: soil quality, slope gradient,

precipitation, NDVI values, and distance to water sources. The selection of criteria was guided by their relevance to agricultural productivity and data availability, consistent with similar studies in the region (Akinci et al., 2013; Bandyopadhyay et al., 2009).

Each criterion was standardized to a common scale (1-5) where 5 represents the highest suitability and 1 represents the lowest suitability. The standardization thresholds were defined based on literature recommendations (Akinci et al., 2013; Bandyopadhyay et al., 2009) and expert knowledge as shown in Table 1.

Table 1. Standardization thresholds for land suitability criteria

Criterion	Score 5	Score 4	Score 3	Score 2	Score 1
Soil quality	Chernozem, Alluvial	Cambisol	Fluvisol	Vertisol	Skeletal, Hydromorphic
Slope (%)	0-2	2-5	5-8	8-15	>15
Precipitation (mm)	>800	750-800	700-750	650-700	<650
NDVI	>0.7	0.5-0.7	0.3-0.5	0.1-0.3	<0.1
Distance to water (m)	<500	500-1.000	1.000-2.000	2.000-3.000	>3.000

The Analytical Hierarchy Process (AHP) was employed to determine criterion weights through pairwise comparisons, following the methodology established by Saaty (1980) and applied in agricultural land suitability studies by Akinci et al. (2013) and Feizizadeh and Blaschke (2013). A questionnaire based on Saaty’s 9-point scale was distributed to 12 agricultural and soil science experts from Serbian universities and research institutes, including the Faculty of Agriculture in Belgrade, Faculty of Agriculture in Novi Sad, and the Institute for Soil Science. The geometric mean of individual responses was used to construct the final comparison matrix, and weights were derived using the eigenvector method.

The consistency ratio (CR) was calculated to verify the reliability of judgments using the formula:

CR = CI / RI

where CI is the consistency index and RI is the random index. A CR value below 0.10 was considered acceptable (Saaty, 1980).

The final land suitability index (LSI) was calculated using the weighted linear combination:

LSI = Σ (W_i × S_i)

where W_i represents the weight of criterion *i* and S_i represents the standardized score of criterion *i*. The LSI values were reclassified into five suitability classes according to FAO (1976): highly suitable (S1: LSI > 4.0), moderately suitable (S2: LSI 3.0-4.0), marginally suitable (S3: LSI 2.0-3.0), currently not suitable (N1: LSI 1.0-2.0), and permanently not suitable (N2: LSI < 1.0).

All spatial analyses were performed using QGIS 3.34 LTR software (QGIS Development Team, 2023) with Python scripting (GeoPandas, Rasterio libraries) for batch processing and automation. The final maps were produced at 25 m spatial resolution to match the coarsest input dataset.

RESULTS AND DISCUSSION

Criterion Weights

The AHP analysis yielded the criterion weights presented in Table 2. The consistency ratio of 0.047 confirmed the reliability of expert judgments, as it falls well below the acceptable threshold of 0.10.

Table 2. Criterion weights derived from AHP analysis

Criterion	Weight	Rank
Soil quality	0.35	1
Slope	0.25	2
Precipitation	0.18	3
NDVI	0.12	4
Distance to water	0.10	5

Soil quality received the highest weight (0.35), reflecting its fundamental importance for agricultural productivity. This finding is consistent with similar AHP-based land suitability studies where soil-related factors typically receive weights ranging from 0.23 to 0.41 (Akbari et al., 2019; Bandyopadhyay et al., 2009; Akinci et al., 2013).

Spatial Distribution of Criteria

The soil quality map revealed that high-quality agricultural soils (chernozem and alluvial) dominate the central and northern portions of the study area, covering approximately 58% of the total area. These soils are characterized by high organic matter content (2.5-4.0%), good water retention capacity, and favorable pH levels (6.5-7.5), consistent with documented properties of chernozem and alluvial soils in the Pannonian Basin (Pavlović et al., 2017; Hadžić et al., 2002). Lower quality soils are concentrated in the southern hilly terrain and along poorly drained lowlands.

Slope analysis based on EU-DEM data indicated that 72% of the study area has slopes below 5%, favorable for mechanized agriculture. Steeper slopes exceeding 15% are limited to the southern portions (Cer and Iverak mountains), representing approximately 8% of the total area. The predominantly flat terrain in the Mačva plain, characteristic of the Pannonian Basin margin, provides excellent conditions for large-scale crop production (Pavlović et al., 2017).

Precipitation patterns show a gradient from northwest (750 mm) to southeast (850 mm), with the entire study area receiving adequate rainfall for rainfed agriculture. However, seasonal distribution analysis revealed that summer precipitation deficits (June-August average: 180 mm) may limit crop yields in certain years without supplementary irrigation (Gocić and Trajković, 2013).

NDVI analysis from Sentinel-2 imagery demonstrated strong vegetation vigor (NDVI > 0.5) across 65% of agricultural lands during the peak growing season (July 2022). Lower NDVI values were observed in areas with sandy soils along the Drina River and in fields with inadequate irrigation infrastructure. The temporal NDVI analysis revealed significant

interannual variability, with 2022 showing above-average vegetation conditions compared to the 2018-2021 baseline.

Land Suitability Assessment

The integration of weighted criteria produced a land suitability assessment with the distribution of suitability classes presented in Table 3.

Table 3. Distribution of land suitability classes in the Mačva District

Suitability Class	LSI Range	Area (km ²)	Percentage (%)
Highly suitable (S1)	>4.0	1.383	42.3
Moderately suitable (S2)	3.0-4.0	938	28.7
Marginally suitable (S3)	2.0-3.0	621	19.0
Currently not suitable (N1)	1.0-2.0	262	8.0
Permanently not suitable (N2)	<1.0	66	2.0

Highly suitable lands (S1) cover 1.383 km² (42.3% of the study area), concentrated in the Mačva plain where optimal soil, slope, and water availability conditions converge. These areas are currently utilized primarily for intensive crop production including maize, wheat, and sugar beet. The spatial clustering of S1 lands along the Sava River floodplain reflects the high agricultural potential of alluvial soils.

Moderately suitable lands (S2) encompass 938 km² (28.7%), located in transitional zones between the alluvial plains and hilly terrain. These areas are suitable for a range of crops with appropriate management practices, including fruit orchards and vegetable production. With targeted investments in soil improvement and irrigation, portions of S2 land could potentially be upgraded to S1 status.

Marginally suitable lands (S3) cover 621 km² (19.0%), primarily in areas with soil limitations or steeper slopes. These lands require improvement measures such as drainage, irrigation, or erosion control for sustainable agricultural use. Alternative land uses such as pasture, agroforestry, or organic farming may be more appropriate for these areas.

Currently not suitable lands (N1) represent 262 km² (8.0%), mainly in areas with severe slope or soil limitations. With significant investment in land improvement, some portions may be converted to agricultural use. However, the cost-benefit analysis should be carefully considered before undertaking such investments.

Permanently not suitable lands (N2) cover only 66 km² (2.0%), consisting of built-up areas, water bodies, protected areas, and extremely steep terrain where agricultural use is not feasible or permitted.

Comparison with Current Land Use

Overlay analysis between the suitability map and current land use revealed that approximately 89% of highly suitable lands (S1) are currently under agricultural use, indicating generally appropriate land allocation. However, 11% of S1 lands are

underutilized or converted to non-agricultural uses (settlements, infrastructure), representing potential for agricultural expansion or protection through zoning policies.

Conversely, approximately 15% of marginally suitable lands (S3) are under intensive cultivation, suggesting potential sustainability concerns. These areas may benefit from conversion to less intensive uses such as pasture or agroforestry systems. The mismatch between suitability and current use highlights opportunities for land use optimization to enhance both productivity and environmental sustainability.

Implications for Sustainable Agriculture

The results support evidence-based agricultural zoning and land use planning at the district level, aligning with recommendations by Rossiter (1996) and FAO (2007) for integrating land evaluation into spatial planning frameworks. The methodology can be readily adapted for other regions in Serbia by adjusting criteria weights based on local conditions and expert knowledge. The integration of freely available satellite data (Sentinel-2) and open-source GIS software (QGIS) makes the methodology accessible to local planning authorities with limited resources.

Climate change projections suggest increasing frequency of drought events in the region, which may alter suitability patterns in the coming decades (Ruml et al., 2012). According to the World Bank Serbia Country Climate and Development Report, temperatures in Serbia are expected to rise by 3-5°C by the end of the century, with increasing precipitation variability potentially reducing agricultural productivity if irrigation infrastructure is not expanded (World Bank, 2023). Integration of climate scenario analysis into the suitability model represents an important direction for future research.

The study provides valuable inputs for the Strategy of Agriculture and Rural Development of the Republic of Serbia, which emphasizes sustainable management of resources and environmental protection (Government of the Republic of Serbia, 2014). The suitability maps can guide decisions regarding agricultural subsidies, irrigation investments, and land consolidation programs. Furthermore, the methodology supports Serbia's alignment with EU agricultural policies and the Common Agricultural Policy (CAP) requirements for evidence-based land management.

CONCLUSION

This study successfully developed and applied a GIS-based multi-criteria methodology for agricultural land suitability assessment in the Mačva District, Serbia. The integration of Sentinel-2 satellite imagery with environmental datasets through the AHP method provided a comprehensive evaluation of land resources for sustainable agricultural planning.

Key findings indicate that 42.3% of the study area is highly suitable for intensive crop production, while 28.7% is moderately suitable. The methodology identified areas where current land use does not align with inherent suitability, providing guidance for land use optimization. Soil quality and slope emerged as the most influential factors determining agricultural suitability.

The developed framework can be applied to other regions in Serbia and the Western Balkans to support agricultural policy development and sustainable land management. Future research should incorporate climate change scenarios, socioeconomic factors, and crop-specific suitability assessments to enhance the practical applicability of land suitability models.

The study demonstrates the potential of geospatial technologies for supporting the green transformation of agribusiness in Serbia, contributing to the sustainable development goals and climate adaptation strategies in the agricultural sector.

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level, spelt wheat flour has significantly higher antioxidant capacity and concentrations of phenolic compounds and certain minerals (e.g. Cu, Fe, Zn) than common wheat flour (Wang et al., 2020). The same study also reported significant interactions between production protocols (organic vs conventional) and wheat species (common vs spelt wheat) with respect to antioxidant and mineral composition.

Grain yield and seed quality in wheat depends on environmental conditions, genetic factors, crop management practices, and the interaction between these factors (Bansod et al., 2013). Among the measures applied to achieve high yields, the time of sowing is particularly important. Sowing time affects the dynamics of ontogenesis, especially the duration of the vegetative phenophases and the phases of grain formation and filling. The optimal time for sowing winter wheat in the climatic conditions of our country varies and depends on the agro-ecological conditions of individual regions, the timing and quality of basic and pre-sowing tillage, and the characteristics of the variety (Dolijanović et al., 2014). When the seeding date is delayed, the periods from tillering to shooting and from tillering to earing are shortened compared with wheat sown at the optimal date (Podolska and Wyzinska, 2011). Late planting results in poor tillering; when the tillering period is reduced (Joshi et al., 1992), plants produce fewer tillers per plant, with lower grain weight and fewer grains per plant (El-Gizawy, 2009). An adequate sowing date positively affects grain yield (Podolska and Wyzinska, 2011; Silva et al., 2014), enabling the plants to better adjust their physiology and phenology to environmental conditions (Ribeiro et al., 2009). A delayed sowing date causes an increase in total protein levels in the kernel, as well as increases in the contents of albumins and globulins, α/β -gliadins, γ -gliadins, total gliadins, HMW-GS, LMW-GS, and total glutenins, but does not change the HMW-GS to LMW-GS ratio (Szymańska and Podolska, 2016).

Organic agriculture, as a system of sustainable agricultural production, today represents an indispensable component of a sustainable agricultural system (Šeremešić et al., 2017) in developing value chains for products with high nutritional value and ecological characteristics. Correct production technology in line with organic principles involves the cultivation of intercrops, the use of green manure, compost activators, and especially the application of biofertilizers with highly effective strains of microorganisms that ensure the supply of plants with biogenic elements (Šeremešić et al., 2018).

Maintaining and increasing soil fertility is a key prerequisite for organic production, and the application of fertilization, processing, and crop rotation aims to ensure the sustainability of the entire farm. Plant nutrition in organic production is based on utilizing natural soil fertility, maintained through proper crop rotation, the cultivation of legumes, and the application of compost or manure. Where the farm does not have sufficient nutrients, the use of organic and mineral fertilizers prescribed by law is permitted. Balanced plant nutrition, which influences plant composition, directly affects plant resistance to pathogens and harmful entomofauna. Some research indicates a reduction in damage caused by insects and diseases in organic production (Manojlović, 2022). Microorganisms increase the uptake and accumulation of N, P, Fe, Mn, Zn, and Cu in plant tissues, as well as the levels of antioxidants and photosynthetic pigments (Dragičević et al., 2021). According to Dolijanović et al. (2012), the highest grain yields of spelt wheat were obtained with a combination of organic and microbial fertilizers (5.84 t ha^{-1}), lower yields with a microbiological fertilizer (4.34 t ha^{-1}), while the treatment without fertilizer resulted in the

lowest yield (3.86 t ha^{-1}). However, the complexity of local agroecological conditions indicates that there is no single solution to exploit the genetic potential of the variety (Ugrenović et al., 2018). The aim of this research is to examine the influence of sowing date and fertilizer type on the grain yield of two varieties of spelt in an organic production system.

MATERIAL AND METHODS

The experiment was conducted on the experimental plot of the Research and Development Institute "Tamiš" in Pančevo, on a certified plot for organic production. Only approved inputs for plant nutrition (organic and microbiological fertilizers) were used in accordance with organic production standards. Two spelt varieties were included in the study: Nirvana and Ostro, both suitable for organic production. The experiment took place in 2023/24 as part of a multi-field crop rotation, with triticale (*Triticosecale*) as the main preceding crop. The role of the pre-crop was to suppress weed species through dense sowing and to leave the soil weed-free. Before sowing, the seeds were treated with Fusarix (a biofungicide used to control phytopathogenic fungi, particularly *Fusarium* sp.) and Slavol to ensure seed protection. In the organic cultivation system, preference is given to sowing chaff seed, as the chaff provides additional protection against soil pathogens.

During basic soil tillage in the autumn, the organic fertilizer Guanito was applied at 600 kg ha^{-1} and Unimax at 150 kg ha^{-1} . Pre-sowing soil preparation was carried out with a seeder. Guanito is a pelletised organic fertilizer with a high phosphorus content; its primary raw material is organic matter from Guano birds from Peru, supplemented by other organic substances such as chicken manure. It is characterized by an extremely high phosphorus content in organic form, a low salt level, and a slightly acidic pH value ($\text{pH} = 6.5$). Its composition is: 6% N, 15% P_2O_5 , 3% K_2O , 27.5% C, C/N ratio 4.6, and 3.5% humic acids. Unimax is a microbiological preparation containing bacteria (*Bacillus megatherium* $3 \times 10^7 \text{ cfu cm}^{-3}$, *Azotobacter chroococcum* sp. $1 \times 10^7 \text{ cfu cm}^{-3}$) applied to natural zeolite. These bacteria have high enzyme activity, are gradually released from the granules during vegetation, and break down organic nitrogen and phosphorus compounds into forms accessible to plants.

Sowing was carried out in two periods: the first on 16 October 2023, and the second 15 days later, on 31 October 2023. The seed rate was 280 kg ha^{-1} . After sowing, rolling was performed to ensure better contact between the seeds and the soil and to optimize soil moisture utilization.

The layout of the plots in the experiment was arranged according to the split-plot design with four replications. The area of the sample plot was 510 m^2 , the calculation plot was 18 m^2 , and the elementary plot was 4.5 m^2 . After establishing the sample, an isolation belt ("buffer zone") was sown, where a coarse grain was also used. The purpose of the isolation belt was to separate the test plots from neighbouring plots and the local road, as a preventive measure recommended in organic production.

In spring, during the budding phase, the crop was foliar-fed with the microbiological fertilizer Slavol at a rate of 7 l ha^{-1} . Slavol is an innovative biopreparation based on microorganisms. The preparation is in a liquid state and contains bacteria (*Bacillus*

megatherium, *Bacillus licheniformis*, *Bacillus subtilis*, *Azotobacter chroococcum*, *Azotobacter vinelandii*, *Derxia* sp.), natural vitamins, enzymes, and growth stimulators. Bacteria on the root system assists in plant nutrition by converting organic and difficult-to-dissolve compounds into accessible forms and delivering them directly to the plant root system.

Harvesting with a grain harvester (Winterstieger) was carried out at the end of June, and the grain yield was measured and adjusted to 14% moisture. The results obtained were statistically analyzed using three-factor analysis of variance (ANOVA) with the F-test, and differences between mean values were determined by the LSD test.

Meteorological Conditions During the Investigation Period

Weather conditions significantly affect the morphological and economic properties of spelt (Glamočlija et al., 2013; Janković et al., 2015). High air temperatures in October, with little precipitation, marked the beginning of the 2023/2024 production year (Table 1). The first half of November was characterized by constant heavy rain, while the temperature of the sowing layer of the soil was favorable for the development of certain winter crops sown at optimal dates. In December, thermal conditions allowed relatively good development and preparation of winter crops for the period of winter dormancy. January was warmer and drier than the ten-year average, and February was also marked by a lack of precipitation and warmer weather. In April, slightly less precipitation was recorded compared to the average for this month. At the beginning of May, favorable temperature conditions in most production areas, combined with average precipitation, enabled intensified growth and the start of wheat heading. In mid-June, high temperatures accelerated the ripening stages of spelt, while rainfall slightly prolonged the harvest.

Table 1. Meteorological conditions in the area of Pančevo

Year/months		X	XI	XII	I	II	III	IV	V	VI	Average/Sum
2023/2024	°C	16.6	8.3	5.2	2.4	9.8	11.1	15.9	18.9	24.8	12.5
	mm	20.4	108.3	29.9	38.8	5.3	24.0	30.8	102.1	94.4	533.0
2010-2019	°C	13.7	9.3	3.7	2.2	4.1	9.1	14.5	18.2	22.6	10.8
	mm	48.9	39.3	40.6	56.7	50.9	54.7	48.4	110.0	85.3	591.5

RESULTS AND DISCUSSION

Table 2 presents the grain yield results for two spelt varieties (Nirvana and Ostro) according to sowing date and type of fertilizer. Statistical analysis of the data showed highly significant differences in grain yield depending on all examined factors and their interactions. Higher grain yields at the study site were achieved with the Ostro variety, particularly in treatments with individual fertilizer applications.

Based on the data in Table 2, it can be noted that later sowing times resulted in better grain yields for both tested varieties. In the Nirvana variety, sowing time showed a statistically very significant difference, while in the Ostro variety, there was a statistically significant difference in grain yield.

Table 2. The influence of different types of fertilizers, their combinations and the date of sowing on the grain yield of Nirvana and Ostro varieties (t ha⁻¹)

Varieties	Nirvana			Ostro		
Fertiliser/date of sowing	first	second	Average	first	second	Average
Control	7.38	8.48	7.93 ^{ab}	8.48	8.66	8.57 ^{ab}
Unimax	7.56	8.56	8.06 ^a	7.93	8.10	8.02 ^b
Guanito	6.78	8.67	7.73 ^b	8.17	8.17	8.17 ^b
Guanito + Unimax	6.96	8.36	7.66 ^b	7.08	8.02	7.55 ^c
Guanito+Unimax+Slavol	6.76	7.75	7.26 ^c	8.47	9.29	8.88 ^a
Average	7.09	8.36	7.73	8.03	8.45	8.24
P value	A	B	C	AB	AC	BC ABC
	**	**	*	*	*	ns ns

A-varieties; B-sowing date; C-type of fertilizer; Different letters indicate significant differences; * $p < 0.05$; ** $p < 0.01$; ns-no statistical differences.

Differences in spelt grain yield depending on the applied fertilizers were statistically highly significant. The combined application of organic and microbiological fertilizers produced good results, especially in the second sowing period for both varieties. The lowest grain yields for the Nirvana variety were recorded with the combination of all tested fertilizers, whereas the opposite trend was observed for the Ostro variety. It can be concluded that the Ostro variety is characterized by more efficient use of soil nutrients. Optimal grain yields in the control variants indicate the good potential fertility of the soil on which the spelt crop is grown, as well as the effect of the selected crop rotation and other measures.

According to Janković et al. (2013), the highest yields of spelt wheat can be achieved on chernozem soil, but due to its lower requirements, it is often produced under restricted agroecological conditions. Earlier studies indicated that sowing date plays a significant role in achieving higher yields, as late sowing shortens the growing period and results in poor crop preparation for the winter (Protić et al., 2008). In a three-year trial, Ugrenović (2013) found the highest spelt wheat yield with the first sowing date (5 October), while delayed sowing reduced yield by 4.0 to 19.7%. Lacko-Bartošová et al. (2010) also found high variation in spelt wheat yield depending on climatic conditions. Spelt wheat has lower requirements in terms of agroecological conditions, but is also less tolerant to drought (Ugrenović, 2013). In dry seasons, yields are significantly lower, primarily due to a lack of nutrient availability under low fertilization.

Pospišil et al. (2014) examined the influence of sowing rate on the yield of spelt, varieties Ostro and Nirvana. They found that the Ostro variety produced significantly higher 1000-grain weight and yield compared to the Nirvana variety, which is consistent with the results of our research. In the aforementioned trial, the grain yield of the Nirvana variety ranged from 4.92 to 6.92 t ha⁻¹ in a two-year study in Croatia, while the yield of the Ostro variety was always over 7 t ha⁻¹. Dolijanović et al. (2014), observing average two-year yields, noted a statistically significant difference depending on feeding (3.80:3.94 t ha⁻¹). Application of only microbiological fertilizers increased yields compared to the control but not compared to other variants in which organic fertilizers or breeders were included.

CONCLUSION

The yield of winter spelt grain was found to depend on the sowing date, fertilizer, and especially on the different cultivars. In both tested varieties, a higher grain yield was obtained in the second sowing period. The yields of grain harvested from spelt grown after triticale were highest in the full treatments with fertilizer (a combination of organic and microbiological fertilizers). The lowest grain yields in both sowing dates and both varieties were obtained with the Guanito+Unimax combination. The yield of the winter spelt grain cultivar Ostro was higher than that of cultivar Nirvana in all variants.

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THE ROLE OF THE SEASN NETWORK IN STRENGTHENING AKIS DEVELOPMENT IN EU AND NON-EU COUNTRIES: A COMPARATIVE REVIEW

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Abstract: Agricultural Knowledge and Innovation Systems (AKIS) are a central element of European agricultural policy, enabling knowledge and innovation to circulate effectively among researchers, advisors, educational institutions, and farmers. In Southeast Europe, AKIS structures have developed unevenly, revealing clear differences between EU Member States and countries of the Western Balkans. Slovenia represents a well-integrated AKIS, where cooperation between advisory services, universities, and research institutions supports rapid innovation uptake, strengthened by digital tools and EU-funded projects. Austria and Croatia show similar patterns, with structured advisory systems that link policy, research, and practice. In contrast, AKIS systems in non-EU SEASN countries remain fragmented. Bosnia and Herzegovina face limited coordination between advisory services and research institutions, resulting in slow knowledge transfer. Serbia's AKIS is still emerging and heavily shaped by individual projects, with inconsistent institutional collaboration. Comparable challenges persist across the Western Balkans, including gaps in digitalisation, innovation support, and advisory competencies. Within this context, the South Eastern European Advisory Service Network (SEASN) serves as a transnational bridge connecting diverse AKIS environments. SEASN strengthens regional knowledge flows, improves advisory competence, and encourages participation in European projects. By linking countries with well-developed AKIS structures to those still forming them, SEASN facilitates gradual alignment with European standards and supports broader regional cooperation and innovation capacity.

Keywords: SEASN network, Agricultural Knowledge and Innovation Systems (AKIS)

INTRODUCTION

Agricultural Knowledge and Innovation System (AKIS) refers to a network of organisations, institutions, and individuals involved in the generation, exchange, and application of knowledge and innovation in agriculture (*AKIS | EU CAP Network*, 2025). The AKIS concept is widely used to identify, analyse, and assess the diversity of actors in agriculture, as well as communication, interaction, and knowledge exchange in innovation among them. The identification of such actors and building of the network provides a framework that allows the mapping of the institutional settings, coordination structure, and policy environments shaping innovation at national and regional levels. Unlike linear knowledge exchange models, AKIS emphasises interaction, learning, and feedback among

multiple agricultural actors, including advisory services, research institutions, farmers, and policy bodies (Knierim et al., 2015).

The formation of AKIS can be explained by the increasing complexity of agricultural systems and the growing inadequacy of top-down models based on the one-way dissemination of knowledge. Such a linear model proved insufficient to address challenges related to climate change, environmental sustainability, development in agricultural technology, digitalisation, and market volatility (FAO, 2025). From a systems perspective, meaningful change in complex systems rarely occurs through isolated interventions or adjustments of individual parameters. Meadows (1999) suggests that the most effective (high-leverage) points in complex systems are information flows, feedback loops, rules, and system goals, rather than in simple changes in inputs or outputs. Traditional extension approaches mainly focused on high-impact inputs or outputs, and therefore, it was harder to achieve broader, systemic change. The AKIS concept responds to this challenge by strengthening knowledge and information flow, by strengthening interaction between research, advisory service, and farmers, thereby targeting higher-leverage points within agricultural systems and enabling more adaptive and innovation-oriented development (Knierim et al., 2015).

AKIS became a mandatory component in EU Member States' CAP Strategic Plans under the 2023-2027 Common Agricultural Policy (CAP), as a tool aimed at strengthening innovation capacity and improving the effectiveness of investments in agricultural and rural development. The European Commission highlighted that although significant resources are invested in development, knowledge flow often remains fragmented and insufficiently translated into practice. This mandate addresses the need for strengthening innovations to be translated into practice, and AKIS actors to support CAP goals for sustainability and competitiveness (Fanos et al., 2022; *AKIS | EU CAP Network*, 2025). AKIS represent networks of actors involved in generating, sharing, and applying knowledge and innovation in agriculture, including advisory services, research, education, farmers, and policy-makers. The effectiveness of AKIS depends primarily on the quality of interactions, coordination mechanisms, and feedback loops among these actors. Well-functioning AKIS are characterised by multi-directional knowledge flows and institutionalised cooperation, while weaker systems tend to rely on fragmented and linear knowledge transfer (Knierim et al., 2015).

The South Eastern Europe Advisory Service Network (SEASN) is a transnational platform connecting advisory services, chambers, research institutions, faculties, and NGOs across South-East Europe. SEASN supports capacity building, knowledge exchange, and dissemination of project results, while enabling participation of non-EU members in EU-funded projects. By bringing together countries with different levels of AKIS development, SEASN facilitates mutual learning and acts as a bridge between EU and non-EU AKIS contexts. AKIS in South-East Europe are characterised by considerable diversity and fragmentation, particularly between EU and non-EU countries. Differences are seen in institutional maturity, governance, funding stability, and the role of advisory services. In many non-EU countries, AKIS structures remain project-based or administratively oriented, with weak interaction and limited knowledge flows. Fragmentation reduces innovation uptake and constrains the ability of agricultural systems to respond to sustainability and development challenges.

Aim and Scope of the Paper

This paper analyses and compares AKIS in EU and non-EU SEASN member countries, focusing on the role of advisory services and institutional arrangements. It identifies key strengths, weaknesses, and structural causes of fragmentation, and examines SEASN's role as a bridging mechanism that supports knowledge exchange, capacity building, and the gradual convergence of AKIS in the region.

COMPARATIVE ANALYSIS AKIS EU MEMBER STATES vs. NON-EU MEMBER STATES

Structure and Role of Advisory Service

Recent European Union (EU) reforms of the Common Agricultural Policy (CAP) place a strong emphasis on strategic strengthening of national Agricultural Knowledge and Innovation Systems (AKIS) and promoting knowledge exchange and innovation in agriculture and rural areas (EU 2021/2025). Despite the growing policy importance of AKIS, its concept and governance mechanisms are not yet fully understood or consistently implemented, particularly in regard to the capacity of policy-makers to actively engage in AKIS coordination (Knierim et al., 2015). A comparative overview of national AKIS systems therefore provides valuable insights into how all main AKIS stakeholders (advisory services, researchers, educators and policy makers) are shaped in socio-economic, governmental and historic context (SWG SCAR-AKIS, 2017).

Advisory services are one of the key building blocks of AKIS. Future advisory work increasingly requires a holistic and farm-tailored approach, combining strategic guidance of the farm and penetrating the markets with specialised technical advice. While public advisory services continue to play a key role in many countries, there has been an increasing trend in recent years among farmers to seek additional support from private advisors in specific thematic areas. This emphasises the need for advisors to strengthen their methodological and technological competencies to face on-farm challenges like climate change, sustainability requirements, diversification of farm income and value addition (SWG SCAR-AKIS, 2017).

In both EU and non-EU member countries of SEASN, there is a variation in the institutional framework for advisory services. Farmer-based organizations and agricultural chambers are major players in agricultural advisory and are firmly embedded in stable frameworks in most EU countries. In some non-EU countries within SEASN, agricultural advisory has been and still is, to some extent, centralised, fragmented, and/or project-oriented with little continuity. Though there is a rising role for private sector advisory organisations, generally, public agricultural advisory organisations are still major interfaces for farmers. However, there is little continuity in the capacity for reactions to challenges (SWG SCAR-AKIS, 2017).

Relations and Compatibility Between Research and Innovation and Advising

Different actors of AKIS face different challenges and follow different incentives, which makes cooperation and synergy among them difficult. Education is often weakly linked to

research, advisory services, and business. Stronger cooperation and networking between researchers, advisors, and farmers is essential, as applied research is often not directly applicable at the farm level. Farmers and food businesses should have a stronger role in setting research priorities, not only in receiving research results. For this reason, a clear distinction is needed between science-driven research and innovation-driven research (DIGI-AGRI, 2009).

The European Innovation Partnership (EIP) for agriculture follows an interactive innovation model, which goes beyond the simple transfer of knowledge from research to practice. It promotes bottom-up cooperation between farmers, advisors, researchers, businesses, and other actors through Operational Groups and Multi-Actor Projects. This approach supports knowledge exchange, uses practical experience, and helps better target research to real needs (European Commission, 2025).

Public support is also needed for a strong “back-office” that connects advisory services with research. Public policy objectives in areas such as research impact, educational and training services, public goods such as climate change and biodiversity, and supporting digital adaptation. It should translate scientific results into practical and understandable information for farmers and advisors, at the same time collecting needs from farmers to inform future research and innovation programmes. In this way, a back-office can improve connectivity, sustainability, and cooperation in the AKIS whole system (SCAR, 2019).

AKIS Analysis in the “SEASN Region”

AKIS Systems in EU Member SEASN Countries

AKIS systems in EU member states that are members of SEASN are generally characterised by higher institutional maturity, stable governance structures, and clearer division of roles among advisory services, research, education, and policy actors.

In Austria, the decentralized AKIS, centered on regional agricultural chambers, enables regionally adapted advisory services and strong links between farmers, research, and support institutions. The combination of public and private advisory services, together with institutionalised cooperation with universities and research centres, explains the system’s stability and effective knowledge flows (Florian Herzog et al., 2024).

In Bulgaria, the AKIS remains centralised under the Ministry of Agriculture and the National Agricultural Advisory Service. Advisory work focuses mainly on CAP compliance and administrative support, which ensures regulatory alignment but limits interactive, demand-driven innovation. Weak digital integration further constrains knowledge exchange, although EU-funded projects increasingly address these shortcomings (Todorova, 2024).

In Croatia, the AKIS is still developing, with advisory services coordinated by the Ministry of Agriculture. Advisors act as intermediaries between research and practice, but the system remains partly project based. Similar to Bulgaria, EU projects play an important role in introducing digital tools and interactive innovation approaches, compensating for limited structural integration (Lelaković et al., 2024).

In Greece, the AKIS is fragmented, despite recent progress in interactive innovation and advisory reform. Universities and research institutes contribute actively to knowledge exchange, but impartial advisory services remain weak. The dominance of commercially oriented private advisors undermines farmers' trust, resulting in limited advisory capacity and weak knowledge transfer (Koutsouris et al., 2024).

In Hungary, the AKIS is relatively well organised and coordinated by the Ministry of Agriculture and the Hungarian Chamber of Agriculture. Advisory services serve as a stable bridge between research, policy, and practice, providing farm-tailored and impartial advice. Although digital tools are increasingly used, further development of participatory approaches is needed (Jakab Gáborné et al., 2024).

In Slovenia, the AKIS is highly integrated, with the Slovenian Chamber of Agriculture and Forestry as the central advisory body, with the Ministry of Agriculture, Forestry and Food as the coordinating body. Strong links between advisory services and research institutions, combined with targeted AKIS interventions under the CAP Strategic Plan, support efficient knowledge flows and innovation uptake through stable public funding and digital platforms (Hrovatič, 2020).

AKIS Systems in Non-EU SEASN Countries

In non-EU SEASN countries, AKIS systems are generally less institutionalised and more fragmented. This reflects transitional policy contexts, limited and unstable public funding, and weak coordination mechanisms among key actors. In some countries, advisory services often operate in administrative or project-based frameworks, which constrain systematic knowledge exchange and long-term innovation support.

In Bosnia and Herzegovina, AKIS structures are highly fragmented due to strong entity-level autonomy. In the Republic of Srpska, coordination between research institutions, advisory services, and farmers is weak, and systematic knowledge exchange is largely absent. Advisory services are organised within the Ministry of Agriculture and mainly perform administrative tasks, which limit the provision of farm-tailored and impartial advice. Farm demonstrations partially bridge research and practice, but innovation uptake remains limited due to weak feedback mechanisms. At the national level, Bosnia and Herzegovina lacks coordination among AKIS actors. The country consists of two entities, the Federation of Bosnia and Herzegovina and the Republic of Srpska, and the Brčko District, each with its own institutional system. The absence of state-level ministries for agriculture, education, and science, combined with limited funding, represents a major barrier to stable knowledge transfer. Strengthening AKIS would require decentralised but better-coordinated systems at the entity level, similar to models in Austria or Germany.

In Serbia, the AKIS has largely remained unchanged and continues to rely on secondary and higher education, along with additional specialised training. Although numerous publicly funded institutions are involved in education, research, and information provision, coordination among them is weak, and knowledge transfer does not sufficiently meet farmers' needs. The limited role of private advisory services, NGOs, cooperatives, and producer organisations further contributes to system instability. Innovation is mainly promoted through public subsidies and demonstration activities, but weak institutional

cooperation and the lack of a stable interactive framework reduce long-term effectiveness (Stanković, 2024).

In Kosovo, the AKIS is evolving within a decentralised framework involving the Ministry of Agriculture, private advisors, universities, and NGOs. A strategic plan and a digital advisory platform support coordination, transparency, and professional development. Advisory services are delivered through public institutions and civil society, with private and NGO actors providing specialised support. Despite challenges related to limited funding and institutional fragmentation, digitalisation and strategic partnerships are driving progress, giving the system strong potential for inclusive and innovation-driven agricultural development.

In Montenegro, the AKIS is not yet fully established, but institutional capacity and interest exist. Most relevant institutions are public, placing the Ministry of Agriculture and Rural Development in a central coordinating role. Advisory services mainly provide technical support, while knowledge transfer remains limited. Further development requires a shift towards more innovative and demand-driven advisory approaches, supported by the establishment of a dedicated AKIS unit within the ministry to improve coordination, financing, and links among key actors (Hrovatić et. al., 2021).

In North Macedonia, the AKIS is under development, led by the Ministry of Agriculture and the National Extension Agency, and supported by EU-funded modernisation efforts. Legal reforms under the Law on the Advisory System have enabled professionalisation and digital integration, while training programmes and mobile advisory platforms are being introduced, including through SEASN-related projects. Despite this progress, the system remains fragmented, with unclear institutional roles limiting coordination and knowledge flows, indicating the need for further restructuring.

Comparative Synthesis of AKIS Characteristics in EU and Non-EU SEASN Countries

Comparison of AKIS structures in EU and non-EU SEASN countries (Annexe 1) shows that there are evident differences concerning the institutional development in both models. In fact, the structures that are in the EU member states are much more institutionalised and stable, with better coordination and a central position of professional advice services. These structures allow for a higher degree of knowledge flow between research, advisory services, and practices.

By contrast, AKIS structures in the non-EU SEASN member states are still relatively emerging or fractured, often project-based with a lack of institutional persistence. Advisory services tend to lack a systematic and institutional design, and thus, the knowledge streams tend to be weaker and more linear. Financing volatility and the absence of digitalisation affect capacity building.

In general, the differences that have been identified are a function of differences in the level of institution and policy alignment and not innovation capability per se, which lends weight to the notion that the development of an AKIS is a process and not a transition.

THE ROLE OF ADVISORY WORK AND EDUCATION IN SHAPING FUTURE AGRICULTURE, FORESTRY AND FOOD SYSTEMS

Agricultural, forestry and food sectors in Europe are increasingly confronted with complex and conflicting challenges, such as climate change, protecting biodiversity, food security and social demands. Addressing these challenges requires strong and well-functioning advisory and education systems that can effectively support farmers and other actors in effecting transitions in systems, such as AKIS. Advisory service networks (IALB, EUFRAS and SEASN) in Europe have highlighted several key areas in a shared position paper that are essential for the future development of key stakeholders, including effective research and knowledge transfer, giving independent and high-quality advice, methodological competencies, digitalisation and the use of artificial intelligence (AI), financing and bureaucratic hurdles (IALB et al., 2025).

Given the diversity of social interest and policy objectives, the public sector is an important factor in supporting advisory services, education, networking and knowledge exchange among AKIS stakeholders (EU CAP Network, 2024). Publicly supported advisory systems are necessary not only to promote issues of public interest, but to support the practical implementation of sustainability requirements at the farm level. Importantly, publicly supported high-quality advice is necessary to sustain social, environmental, climate protection and animal welfare (*AKIS Practices under CAP*, 2025; IALB et al., 2025).

The close linking of research, education and advisory services is a key factor in sustainable and innovative agriculture. However, the agricultural, together with forestry and food sectors, should include economic and social sustainability. This integration enables more effective knowledge transfer into practice and supports the uptake of innovation that addresses both productivity, environmental and economic sustainability goals. To achieve this, sufficient and stable public funding is needed, particularly for advisory services and education, to ensure their collaboration, and their quality, independence and long-term impact (EU CAP Network, 2024; IALB et al., 2025).

Often commonly emerging obstacles in everyday advisory, research and education work is the ever-complex bureaucratic approach. This obstacle can destabilize efficient knowledge exchange and practical support. Reducing administrative burdens and strengthening existing advisory frameworks are a necessary step toward improving the quality and the independence of advice, and with that, system effectiveness. In this context, three European Advisory Service Networks (IALB, EUFRAS and SEASN), with their activities, target further development of agricultural and rural advisory services and education with public support, promoting a whole-farm approach that enhances economic viability, environmental sustainability and social resilience (IALB et al., 2025).

SEASN'S BRIDGING ROLE IN THE DEVELOPMENT OF AKIS

The overview of AKIS systems of SEASN member countries shows a high diversity in their structure between EU and non-EU contexts. On the other hand, it reveals emerging patterns and shared challenges. EU member states such as Austria, Slovenia, and Hungary showcase more institutionalised and integrated AKIS, specified by established interaction between advisory services, research institutions, education, and practice, while still

promoting the use of digital tools. In contrast, AKIS systems in non-EU SEASN countries are often still emerging, due to the establishment of AKIS systems in pre-accession countries. Their systems are often fragmented, or project-based, with weaker coordination mechanisms, limited continuity, and poorly established connections between research, advisory service, and farmers.

Although there are visible differences between non-EU countries' AKISs, an overview of them indicates that fragmentation, insufficient coordination, and weak knowledge flows are present. Even in EU member states, challenges occur in terms of inter-institutional cooperation, digital integration, effective translation of research into practice, and interrupted communication in a bottom-up approach. This suggests that AKIS development should not be understood as a linear transition from underdeveloped to fully developed (or functional), but rather as a continuous process of developing and evolving, while adapting to current policy, environmental, and socio-economic demands.

Within this aspect of continuous development, SEASN plays an important role as a bridging mechanism between EU and non-EU AKIS systems. The inclusion of European members of two different policy contexts and environmental frameworks creates a unique space where they can interact and work within a single network. This enables mutual learning processes in which EU member states contribute experience related to CAP implementation, AKIS governance, and alignment with Green Deal objectives, which is particularly beneficial for pre-accession countries. On the other hand, non-EU countries can provide practical insights derived from more flexible, locally adapted, and often project- and innovation-driven approaches.

The SEASN plays an important role in the development of AKIS in South-East Europe by strengthening advisory capacities and fostering innovation-oriented knowledge exchange. Through joint training, dissemination of EU project results, and cross-border cooperation, SEASN improves knowledge flows among advisory services, research institutions, and education systems. Importantly, SEASN enables the participation of non-EU countries in European projects, thereby contributing to the gradual alignment of different AKIS contexts and the emergence of a transnational AKIS space.

By implementation of its activities, SEASN facilitates cross-border exchange of knowledge and practice among advisors, researchers, and educators. This supports the gradual convergence of AKIS principles without imposing the development of uniform models but rather presenting and sharing good practices of the AKIS system and its leverage points. With this, SEASN promotes contextual adaptation, allowing policy instruments, methodologies, and digital solutions to be tested and adjusted in a national setting. Rhetorically, SEASN functions as an intermediary arena where European agricultural and sustainability objectives are translated into regionally relevant practices, while national experiences give feedback into broader European discussion on AKIS development.

When we compare and analyse AKISes of SEASN member countries, we see that strong advisory service and education represent a high-impact leverage point for strengthening national AKIS. As emphasised in a joint position paper of IALB, EFRAS, and SEASN, presented to the European Commission, advisory work and education are crucial for addressing complex challenges such as climate change, agricultural sustainability, food

security and environmental protection. This is why the mentioned stakeholders should be a key focus in the CAP plan. Publicly funded advisory services are essential not only to disseminate technical knowledge, but also to mediate conflicting societal objectives and to support farms in balancing agricultural, environmental, economic and social sustainability. Considering both EU and non-EU countries, we can identify that closer integration of research, education and advisory services is essential for resilient agricultural, forestry and food systems. Key importance also lies in strengthening institutional cooperation, which leads to more effective knowledge flow, and reducing bureaucratic barriers, investing in digitalisation and ensuring stable public financing. All factors mentioned contribute to an effective AKIS functioning. Within this framework, SEASN, together with other advisory service networks, contributes by reinforcing regional cooperation, amplifying the advisory perspective in European policy recommendations, and supporting the long-term sustainability of advisory services as a strategic investment rather than a cost.

CONCLUSION

This paper analysed Agricultural Knowledge and Innovation Systems (AKIS) in EU and non-EU SEASN member countries to identify where systems differ, what their main weaknesses are, and why these differences persist. The analysis shows that EU member states generally have more stable and integrated AKIS, while non-EU countries face fragmented and less institutionalised systems. The key difference lies in institutional organisation and the role of advisory services. In EU countries, advisory services are well embedded within AKIS and closely linked to research, education, and policy, which enables effective knowledge transfer and innovation uptake. In contrast, in many non-EU countries, advisory services operate in administrative or project-based frameworks, with weak coordination and limited continuity. As a result, knowledge transfer remains inconsistent and often fails to meet farmers' needs.

Within this context, SEASN emerges as a key bridging mechanism between diverse AKIS environments. By connecting advisory services, research institutions, and educational actors from both EU and non-EU countries, SEASN enables the transfer of experience, practices, and governance approaches across different policy contexts. EU member states contribute institutional experience related to CAP implementation and AKIS governance, while non-EU countries bring flexible, locally adapted, and often innovation-driven approaches. This two-way exchange supports mutual learning and gradual convergence without imposing uniform models. Through capacity building, joint trainings, dissemination of project results, and participation in EU-funded initiatives, SEASN strengthens advisory competencies and improves knowledge flows across the region. As advisory services represent a central leverage point for effective AKIS, SEASN's bridging role contributes to reducing fragmentation, enhancing coordination, and supporting the long-term development of resilient and innovation-oriented AKIS in South-East Europe.

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ANNEX 1

Comparative synthesis of key characteristics of Agricultural Knowledge and Innovation Systems (AKIS) in EU and non-EU SEASN countries

AKIS dimension	EU SEASN countries	Non-EU SEASN countries
Institutional maturity	Largely institutionalised and stable AKIS structures (e.g. Slovenia, Austria, Hungary)	Emerging, incomplete or fragmented AKIS structures (e.g. Bosnia and Herzegovina, Serbia, Montenegro)
Governance and coordination	Clear governance frameworks aligned with CAP; coordination often shared between ministries and chambers (e.g. Slovenia, Austria)	Complex or centralised governance, often with weak coordination and limited national-level integration
Role of advisory services	Central and professionalised role within AKIS, with recognised institutional authority (e.g. Slovenia, Hungary)	Advisory services often operate ad hoc, project-based or with a limited institutional mandate
Research-advisory interaction	Formalised, continuous and embedded in institutional arrangements	Sporadic, weak or dependent on individual projects and initiatives (e.g. Bosnia and Herzegovina, North Macedonia)
Knowledge flow	Multi-directional and systematic knowledge exchange e.g. Slovenia, Austria)	Predominantly linear, intermittent and discontinuous knowledge transfer
Funding stability	Relatively stable public funding, largely supported by CAP instruments and EU programmes	Short-term and mixed funding sources, often donor- or project-driven (e.g. Kosovo, Montenegro)
Digitalisation	Increasingly integrated digital platforms and advisory tools	Uneven digital development, with limited access, capacity or infrastructure (e.g. Bosnia and Herzegovina)
Innovation support	Embedded within long-term strategies and institutional frameworks	Often innovation-driven but fragmented and lacking continuity (e.g. Serbia, Kosovo)
Policy feedback mechanisms	Established bottom-up feedback channels from practice to policy	Weak, informal or missing feedback mechanisms
Key drivers	EU policy alignment, institutional continuity, stable advisory systems	EU pre-accession incentives, donor-funded projects, local flexibility (e.g. Serbia, Kosovo, North Macedonia)
Key challenges	Increasing system complexity, coordination across multiple actors, capacity pressures	Fragmentation, limited coordination, lack of continuity and institutional stability (e.g. Bosnia and Herzegovina, Montenegro)

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PLANT GROWING IN HYDROPONIC SYSTEM: CASE OF STUDY

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Abstract: Hydroponics is an innovative plant production system in which crops are cultivated in a nutrient, often with the support of inert substrates such as expanded clay, perlite, coconut fiber or rockwool. This method is typically implemented in controlled environments, including greenhouses or high tunnels, where key growth parameters (pH, electrical conductivity, nutrient concentration, temperature, light intensity, oxygen availability and air circulation) can be precisely regulated. Although hydroponic systems require higher initial investments, these costs are gradually offset through increased productivity and more efficient resource use. As a green innovation, hydroponics reduces dependence on climatic variability, limits exposure to pests and pathogens and supports year-round production with reduced water consumption and environmental impact. As part of this research, a case study was conducted to evaluate hydroponic cultivation under simplified, home-scale conditions. The goal was to identify the most critical control points in the system, including the sensitivity of pH and electrical conductivity adjustments, nutrient balance, temperature fluctuations and light availability. Several combinations of environmental and nutrient conditions were tested to determine which setups yield the most stable plant growth and highest biomass production. The results highlight the importance of continuous monitoring, particularly during early developmental stages, and demonstrate that even small deviations in nutrient concentration or environmental parameters can significantly affect plant performance. Findings from the case study provide practical insights into the limitations, risks and optimal management strategies for small-scale hydroponic systems, contributing to a broader understanding of hydroponics as a sustainable and accessible agricultural approach.

Keywords: Climate-smart agriculture, Hydroponics, Nutrient solution management, Sustainable production

INTRODUCTION

Hydroponics refers to cultivating plants in water enriched with essential nutrients rather than in traditional soil. The word itself comes from Greek, combining “hydro” (water) and “ponos” (work). In hydroponic setups, plant roots are typically stabilized using inert substrates such as peat moss, charcoal, gravel, rock wool, perlite, coco peat, or coconut coir. These systems are designed to precisely regulate water, nutrient levels, and oxygen availability, creating conditions that favor optimal plant growth (Rajaseger et al., 2023). Today, hydroponic techniques are applied both in commercial production and in household settings for growing numerous types of crops, including vegetables, fruits, herbs, and ornamental plants. Although soil-free cultivation has ancient origins, the modern form of

hydroponics emerged in the mid-20th century as a response to the need for increased food production in areas where space and resources are limited (Rodríguez-Delfín et al., 2017).

The history of the development of hydroponics, that is, the cultivation of plants without the use of soil, in a nutrient solution, spans a very long period from ancient civilizations to modern, highly automated production systems. Based on the major achievements that stimulated the development of this innovative method, several phases can be distinguished: the ancient and medieval period; the period from the 17th to the 19th century; the period from 1930 to 1950; from 1960 to 1990; and the contemporary phase, from 2000 to the nowadays (Walters et al., 2020). Although it is believed that the Hanging Gardens were created utilizing the first known application of hydroponic cultivation, there are claims that the prototype and beginning of hydroponic is “chinampa” as a raised field on a small artificial island on a freshwater lake surrounded by canals and ditches (Ebel, 2020). The period from the 17-19th century marks an important advancement in the development of hydroponics, as it was during this time that the scientific foundation for this method was established particularly regarding the chemical composition of nutrient solutions, the selection of plant species, and other key aspects of the technique. In 1929, William Frederick Gericke from the University of California, Berkeley, began advocating the application of hydroponic concepts for growing agricultural crops and introduced the term hydroponics, formed from the Greek words for water and labor. A decade later, in 1940, Gericke widely regarded as the pioneer whose work laid the groundwork for all modern hydroponic systems released his book “The Complete Guide to Soilless Gardening.” This publication presented his initial nutrient solution formulas, which included both macro- and micronutrient salts tailored for plants cultivated without soil. Much of his experimental work centered on vegetable crops, with tomatoes being his primary model species (Torabi et al., 2012).

Over the past few decades, hydroponics has evolved into a key component of modern, technology-driven agriculture, incorporating features such as automated sensors, digital monitoring systems, LED-based illumination, and vertically arranged production units. This cultivation method is increasingly central to smart farming strategies, urban food systems, and sustainable agricultural practices. Countries with the most advanced commercial hydroponic sectors include the Netherlands, Japan, Israel, and the United States. Hydroponics has also attracted attention in aerospace research, particularly for growing plants under microgravity conditions. For many years, NASA has carried out extensive studies within its Controlled Ecological Life Support System (CELSS), investigating hydroponics as a potential bioregenerative technology that could support long-term human missions in space (Abeer et al., 2025).

Nowadays, there are several hydroponic techniques, each with multiple variations. Some of them include (Rajaseger, 2023): nutrient film technique (NFT); static solution culture; continuous-flow solution culture; aeroponics; fogponics; passive hydroponics (the Kratky method); Ebb and Flow (flood and drain); the Bengal technique; deep water culture (DWC).

The objective of this paper is to analyze advantages and limitations of hydroponics growing systems and to present a small hydroponic system through a practical case study, with a specific focus on the importance of space setup and equipment in establishing this form of

plant production. The general aim is to contribute to the popularization of hydroponics as a sustainable system of growing plants.

ADVANTAGES AND LIMITATIONS OF HYDROPONIC

Hydroponics has become an essential component of modern agriculture, particularly within the framework of smart farming. This approach provides notable advantages and helps overcome many challenges associated with traditional cultivation practices. Compared to soil-based and even greenhouse production methods, hydroponic systems offer several significant improvements. Efficient use of resources such as water, nutrients, and growing area is one of the major advantages of hydroponic cultivation. Studies (Jones Jr, 2014; Khan, 2018; Rajendran, 2024) show that hydroponic systems can cut water consumption by as much as 90% compared to traditional soil agriculture. Moreover, nutrient solutions can be collected, refreshed, and reused, which supports sustainability and significantly lowers overall waste. When combined with vertical farming approaches, hydroponics also maximizes spatial efficiency, enabling the production of a large number of plants within a relatively small footprint. Hydroponic systems make it possible to grow plants continuously throughout the year, independent of weather patterns or seasonal limitations. Within controlled environments, growers can fine-tune key growth factors such as temperature, humidity, light levels, and nutrient composition. This ensures a steady and reliable food supply, reduces dependence on imports, and strengthens overall food security. Studies (Yee Sin et al., 2023) indicate that hydroponics supports faster plant development and higher yields compared to conventional soil-based farming due to precisely managed growth conditions. Tailoring nutrient solutions and optimizing the root-zone environment significantly enhances plant vigor and overall productivity. Using hydroponics helps lessen the environmental pressures commonly associated with traditional agriculture. Since soil is not required, problems like erosion, nutrient depletion, and soil degradation are minimized. When combined with sustainable practices such as organic pest management, water recycling, and renewable energy hydroponics provides an eco-friendlier and resource-efficient farming approach (Velazquez-Gonzalez et al., 2022). Regarding nutritional quality and flavour, it has been confirmed that precise control of nutrient levels and growing conditions in hydroponic cultivation realize positive effects. Hydroponics creates a growing system that does not rely on soil, which significantly lowers the likelihood of pests and diseases typically transmitted through soil. In such controlled conditions, Integrated Pest Management (IPM) strategies can be applied more efficiently, making greater use of biological control agents and reducing dependence on chemical pesticides. As a result, plants remain healthier and the final produce is safer for consumption. (Handayani et al., 2023). Researchers (Taylor et al., 2012; Ghimire et al., 2023) emphasize relation between hydroponics and urban agriculture due to it allows food production in confined spaces such as rooftops, vertical farms or indoor facilities. Further, local food production positively affects reducing transportation distances, freshness of food and strengthening the local community as well as local involvement and knowledge about sustainable food systems. One more aspect of hydroponics relates to scientific and research importance. It could be a platform for scientific research and innovation in agriculture and space for new techniques investigation, cultivars improving and contemporary approaches for sustainable food production testing. Hydroponic offers possibilities for integrating smart technologies, automation and data analytics contributing to agricultural sustainability and modernization (Monisha et al., 2023).

Although hydroponics offers increased efficiency, sustainability and productivity, overcoming the limitations of traditional agricultural methods, there are some limitations and challenges in regard to pest and diseases control, skill and knowledge, higher set up cost, hot weather and limited oxygenation, sensitivity of plants to even the smallest changes in the growing environment (Pandey et al., 2009). Regarding to pests and disease, situation is contradictory. Soil-borne pests and diseases are largely eliminated in hydroponic crop production. However, these systems introduce other types of risks. In particular, water-borne pathogens may pose a concern, including organisms that represent significant biosecurity threats, such as *Phytophthora* spp. or bacteria harmful to human health. These hazards are especially pronounced in recirculating systems, where pathogens can accumulate over time, making strict sanitation practices essential. Such measures include routine monitoring and treatment of irrigation water. In protected cropping environments, pest pressure may increase because conditions that favor plant growth can also support insect reproduction. This challenge can be managed through well-designed and proactive integrated pest management (IPM) programs. Additionally, the warm and humid conditions typical of covered systems may promote certain fungal diseases, highlighting the need for timely detection and appropriately scheduled control measures (Wootton-Beard, 2019). The primary limitations, however, to the adoption of hydroponic systems are the high initial capital investment and the technical expertise required to manage and operate control systems. Unlike soil-based cultivation, which is relatively tolerant of imprecision and minor errors, hydroponic production relies on highly accurate control of growing conditions, where even small mistakes can lead to significant losses. While enhanced control improves efficiency and productivity, it also introduces a higher level of operational risk. Support and guidance are increasingly available through various organizations, and training opportunities are becoming more accessible. The financial costs of hydroponic systems rise with increasing levels of precision, and the most economically viable technique and scale will vary depending on the crop being grown. Given the wide range of equipment and system designs available, the final choice of a hydroponic system ultimately rests on the individual preferences and objectives of the grower (Kumar et al., 2023).

CASE OF STUDY

Modern agricultural production necessarily requires new and innovative approaches and methods in order to respond to the challenges and demands of sustainable development. A key objective is the production of sufficient quantities of safe and healthy food, while minimizing environmental risks and ensuring economic viability. Official data on the implementation of so-called “green innovations” at farm level indicate that domestic agricultural producers are reluctant to engage in such “experimental” practices. Furthermore, various studies have shown that rural populations, as well as other target groups interested in agricultural production, often lack adequate and relevant information and knowledge about many methods and techniques that align with current sectoral trends and the requirements of the modern market (such as organic and regenerative agriculture, the circular economy, precision agriculture, hydroponics, agroforestry, and aquaculture).

In addition to the general aim of systematizing key information on hydroponics as one of the “green” innovations in agriculture and providing an overview of the status of this method both regionally and globally, this publication through a dedicated section focused on a case study and a detailed analysis of the organization of a hydroponic system in a

small-scale setting pursues the following specific objectives: to introduce this method to individuals; to clearly and simply present its critical points; to propose solutions for overcoming these challenges and to stimulate producers' interest in expanding the use of hydroponics in practice, initially through simpler systems and subsequently through their upgrading and further development.



Figure 1. Explained hydroponic growing system (Own source)

All of observations are based on the pilot project realized in small scale hydroponic growing system (Figure 1). Special attention, in the analysis of this pilot project, is given to the importance of space and equipment for organizing hydroponic plant cultivation in small-scale systems.

Preparation and Equipment of the Facility

For the installation of the hydroponic tent in this case, a cabinet designed to accommodate four hydroponic containers a basement space with a total area of slightly over 6 m² was selected. Thorough cleaning and disinfection of the facility were considered essential, as the presence of pathogens (fungi, mold) could endanger the entire project. Disinsection of the basement was also mandatory while it might not be strictly necessary in some other scenarios, it was nevertheless a prudent preventive measure. The basement housed a substation of the district heating system, which proved to be a significant advantage under winter conditions, as no additional heating of the space was required. During the coldest part of the night, when the heating system was not operating, the temperature in the facility did not fall below 16°C, while during the day it did not exceed 27°C.

However, at certain times this upper temperature limit posed a challenge, as there was a risk that temperatures inside the hydroponic cabinet could be even higher. This issue was addressed by improving ventilation within space.

A smart device, a thermometer and hygrometer were installed in the space and connected to an Android application. The device controlled the ventilation fans and issued alerts whenever temperature or humidity deviated from the desired range. The fans were also linked to the same Android application (Figure 2) via a smart device, in this case a smart switch, allowing ventilation schedules and operating durations to be set according to assessed needs. These applications typically provide hourly, daily and monthly reports, thereby offering full flexibility in decision-making.



Figure 2. Android app to control Smart thermometer and hygrometer (own source)

Preparation for the Growing Space (Chamber)

In this case, the “growing space” was in fact a hydroponic cabinet (chamber) measuring 120 cm in width, 120 cm in height and 60 cm in depth. The frame was constructed from wooden slats with a cross-section of 2×2 cm. Insulation made of polystyrene was installed in the spaces between the slats, and a thicker plastic film was applied over the entire structure, on both sides of each panel, to prevent moisture penetration into the panels and to ensure better sealing, thereby facilitating more precise control of the growing conditions. The front panel consisted of doors that could be opened across the full height and width, allowing easier access to the growing area. Prior to construction, the cabinet was designed using a 3D modeling program to enable accurate and efficient fabrication (Figure 3).

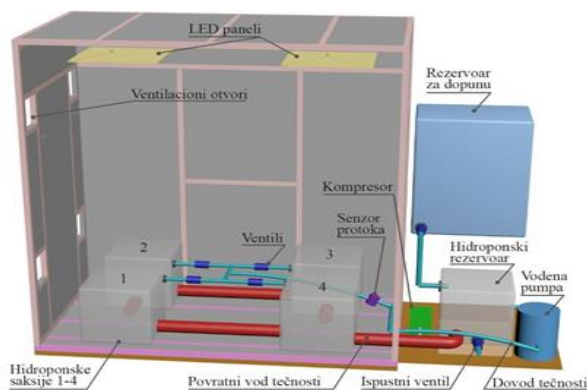


Figure 3. 3D scheme of hydroponic cabinet (Own source)

Under different circumstances, it would have been much simpler to use a ready-made grow box or tent designed for plant cultivation; however, in this particular case, this was not an option due to the limited dimensions of the available space.

Equipping the Growing Space

The hydroponic cabinet needed to be equipped with lighting, ventilation, a humidity control system and a system for oxygenating the hydroponic solution. In the case of greenhouses or glasshouses operating year-round, additional heating systems must also be considered, and it is advisable to include a system for regulating carbon dioxide (CO₂) levels. Many authors wrote about importance of climate control, emphasizing it is essential to maintain the proper temperature, humidity, light and ventilation levels within the hydroponic system to ensure optimal growth (Cherif et al., 2023; Santosh and Gaikwad, 2023).

In this case, plant lighting was provided by two full-spectrum LED panels (Figure 4), each with a power rating of 50 W, which proved to be fully adequate for the dimensions of the cabinet. The LED panels were connected to a smart switch that controlled their operation via an application timer, switching them on and off at predetermined times and thereby ensuring 16 hours of “day” and 8 hours of “night.”

A challenge encountered in this setup was heat generation from the LED panels, which affected the internal temperature of the cabinet. This required certain modifications to the original plan: the number of ventilation fans, each with a diameter of 12 cm, was increased from four to eight, providing sufficient airflow and enabling proper temperature control.

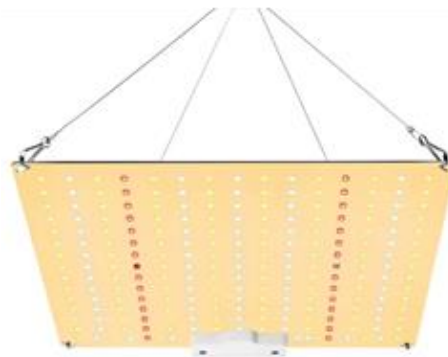


Figure 4. Led panel (<https://hidroponika.co.rs/proizvod/led-grow-panel-30x30-50w-uv-ir/>)

On the inside, the pages were lined reflective aluminum foil in order to let in as much light as possible bounced off and reached the lower parts of the plants. These factors raise the question of energy efficiency of the system. The previous results have pointed out importance of the novel Integrated Hydroponic Greenhouse Model (IBGH) emphasizing that the consideration of lighting heat plays a pivotal role in achieving energy-efficient heating and cooling processes. The findings suggest, further, that an elliptical structure and PVC as a covering material offer practical advantages (Hassine et al., 2024).

Moisture regulation has proven to be a critical point, especially in small closed and well-sealed rooms like our closet. At the initial stage, when plants are still small, it is desirable

for relative humidity (RH) to be in the range of 70-85%, with an optimum of approximately 75%. However, as plants grow, excessive humidity promotes fungal development and plant deterioration; therefore, RH should be maintained at a maximum of about 35-40%. In this case, opening the cabinet doors was not a suitable solution, as each ventilation of the facility (basement) would expose the plants to cold air and cause thermal shock.

The solution was the use of a cabinet dehumidifier that was not a smart device but was equipped with its own temperature and humidity sensors. The unit automatically activated dehumidification and included a relay switch option, allowing a heater or a fan to be connected for temperature adjustment. The dehumidifier had a dedicated drain for the collected liquid, which was discharged outside the cabinet.

Application of the method additional heating, when it is necessary, depends on the climate and construction of the greenhouse or greenhouse and can be: on solid fuel, with heat distribution; passive solar heating; double wall of the greenhouse made of nylon foil into which warm water is pumped air, heated in various ways, in combination with passive solar by heating; insulating blanket, in combination with passive solar heating, which is developed between the double nylon walls of the greenhouse and geothermal heat pumps - the so-called earth pumps

It is recommended to control the amount of carbon dioxide (CO_2), in any closed greenhouse or hydroponic room, during daylight hours, because the increased percentage has a favorable effect on the growth and development of plants. Despite this, the idea of controlling the carbon dioxide content in this project was abandoned because it was not possible to meet the required level of precision. The possibility to “make” some amount of CO_2 , in such cases, is either in the chemical reaction of vinegar and of baking soda or by using sugar mixture, yeast, baking soda and warm water, without vinegar and electric valve. Practically, these methods were tested in this case, with positive results in CO_2 obtaining (Figure 5).

The difficulties with these methods in such small spaces are due to the fact that CO_2 is heavier than air, so for an even distribution within the space, a larger number of fans is needed, for which these spaces are too limited. This factor requests further and detailed investigation due to its contradictory roles in hydroponics growing system. Although the results demonstrate that CO_2 supplementation significantly enhances the growth of leafy greens grown in hydroponic systems, CO_2 enrichment, however, may also affect produce quality, as indicated by lighter leaf coloration and the occurrence of physiological disorders (Singh et al., 2020).

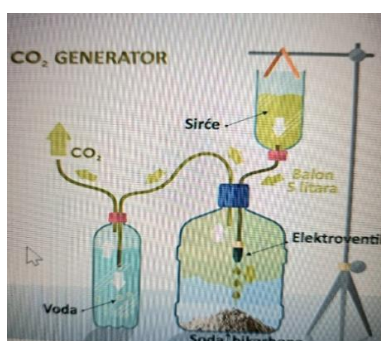


Figure 5. Carbon dioxide generator (Own source)

CONCLUSION

This study confirms hydroponics as an important and sustainable production system that enables efficient use of water, nutrients and space, while allowing year-round crop cultivation under controlled conditions. The case study demonstrated that even small-scale, simplified hydroponic systems can achieve stable plant growth and satisfactory biomass production, provided that critical parameters such as pH, electrical conductivity, temperature, humidity and light are continuously monitored and precisely managed. However, the results also highlight key limitations, including high system sensitivity to minor deviations in environmental and nutrient conditions, technical complexity and the need for adequate knowledge and equipment. Overall, hydroponics represents a promising climate-smart agricultural approach, but its successful application, especially at small scale requires careful system design, constant control and gradual adoption to minimize risks and ensure produce quality.

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DEVELOPMENT OF AN INTELLIGENT DECISION SUPPORT SYSTEM FOR WASTE RECYCLING

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Abstract: The aim of this paper is the development and simulation of an intelligent Decision Support System (DSS) in the field of waste recycling. The proposed model integrates the Random Forest algorithm for classification and prediction with an optimization model that minimizes costs and maximizes revenues from the sale of recycled materials. The database provides input parameters (waste type, quantity, processing cost, revenue), while the user interface enables interaction with the system and the generation of recommendations. The simulation was conducted on hypothetical data for three types of waste (plastic, glass, and metal), applying different recycling strategies. The results demonstrate that the DSS model achieves a positive financial effect, as revenues from sales exceed processing costs, with the greatest contribution observed in the case of metal. These findings confirm that the proposed DSS model can provide economically sustainable recommendations for waste management and serve as a foundation for future research that would include additional waste categories, environmental indicators, and logistical constraints.

Keywords: Decision Support System (DSS), Random Forest, Optimization model, Waste recycling

INTRODUCTION

Urbanization, industrialization, and the expansion of consumer lifestyles have created significant challenges in waste management. With the increasing amounts of municipal and industrial waste being generated, it has become evident that traditional sorting and recycling processes are no longer sufficient for efficient and sustainable resource management (Ibrulj et al., 2025; Negreiros Gomes et al., 2023). Sustainable development requires the application of advanced technologies capable of enhancing existing systems, reducing costs, and improving the accuracy and speed of waste separation processes. One promising alternative to this problem is the application of artificial intelligence. Conventionally, the use of artificial intelligence in waste management has been limited to neural networks for predicting daily waste quantities. In contrast, this study builds on the idea of incorporating advances in artificial intelligence into decision-making systems within the recycling process. The objective is to present a decision support model that can simultaneously satisfy diverse societal criteria primarily ecological and economic, while remaining simple to implement.

Waste logistics and sorting often rely on manual or basic automated processes; however, contemporary technology enables the use of machine learning and data analysis to improve

performance and precision. Within our system, the optimization model plays a crucial role in decision-making by reducing overall process costs, including logistics, storage, and sorting. This model facilitates the identification of the most efficient routes, resource allocation, and loss reduction, thereby significantly contributing to system sustainability. On the other hand, the use of the Random Forest algorithm for waste separation represents an innovative approach to the automatic recognition and differentiation of small waste components, which is essential for improving sorting accuracy and recycling efficiency.

The development of an intelligent decision support system for waste recycling requires the integration of multiple functional components that enable the collection, processing, analysis, and optimization of data relevant to waste management (Wirani et al., 2024). Accordingly, this study focuses on the design of an innovative DSS that integrates an optimization model for minimizing the costs of the recycling process with advanced algorithms for automatic waste separation (Fernando and Baldeovar, 2022). By combining these methods, the goal is to create an integrated system that is not only technically feasible but also economically sustainable, reducing operational costs and increasing recycling performance. Such a system has the potential to advance the waste management industry, contribute to environmental protection, and promote the principles of the circular economy, thereby addressing contemporary sustainability challenges through the application of advanced technologies. The proposed model encompasses four key components: a database, the Random Forest algorithm, an optimization model, and a user interface. The interactions among these components are defined through bidirectional data flows, ensuring dynamic information exchange and adaptive decision-making.

MATERIAL AND METHODS

In order to improve the waste recycling process, an intelligent decision support system has been developed that integrates machine learning techniques with optimization models. The system architecture encompasses the following key components: a database, a user interface, the Random Forest algorithm, and an optimization model. The graphical representation of the model is provided in Figure 1.

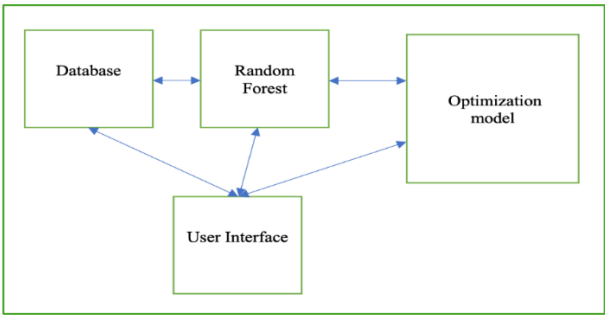


Figure 1. IDSS model, Source: Authors

The database serves as the central repository for storing both input and output information related to waste types, quantities, locations, processing costs, as well as historical data on previous recycling activities. This component enables bidirectional communication with the Random Forest algorithm and the user interface, thereby ensuring the timeliness and relevance of data in the decision-making process (Zhou et al., 2020).

The Random Forest algorithm functions as a mechanism for classification and prediction, employing an ensemble of decision trees to identify patterns within the data. Its application within the system enables:

- classification of waste types according to recycling suitability criteria,
- prediction of optimal waste management strategies based on historical data and
- filtering of relevant inputs for the optimization model.

The algorithm communicates with the database, the user interface, and the optimization model, thereby ensuring multilayered analysis and robust decision-making (Breiman, 2001).

The optimization model utilizes the classification and prediction results generated by the Random Forest algorithm as input parameters for decision-making. The objective of this component is to identify strategies that minimize recycling costs, maximize ecological benefits, and comply with infrastructural and regulatory requirements. The model applies mathematical optimization methods, specifically linear programming, to generate recommendations consistent with defined goals and constraints (Deb, 2001). The objective function can be mathematically expressed as follows:

$$C^r = \bar{n} \sum_{i=1}^m \left(\left(\sum_{j=1}^k C_{i,j}^x r_i \alpha_i x_{i,j} \right) - B_i r_i \alpha_i \right)$$

The objective function is designed to minimize recycling costs while accounting for revenues from the sale of recycled materials. The first term,

$$\sum_{j=1}^4 C_{i,j}^x r_i \alpha_i x_{i,j},$$

represents the total processing costs across all recycling strategies, whereas the second term,

$$-B_i r_i \alpha_i,$$

reduces the overall cost by incorporating revenues from material sales. In this way, the model balances economic profitability with recycling efficiency.

RESULTS AND DISCUSSION

To verify the proposed architecture of the intelligent decision support system (IDSS) for waste recycling, a simulation was conducted using hypothetical data. The simulation included three types of waste (plastic, glass, and metal), three recycling strategies (A, B, C), and the defined objective function, which minimizes costs while accounting for revenues from the sale of recycled materials.

The simulation was carried out under the following assumptions:

- **Plastic:** quantity 120 kg, processing cost 0.5 EUR/kg, revenue 60 EUR, efficiency 0.9,
- **Glass:** quantity 80 kg, processing cost 0.7 EUR/kg, revenue 50 EUR, efficiency 0.85,
- **Metal:** quantity 50 kg, processing cost 0.4 EUR/kg, revenue 70 EUR, efficiency 0.95.

Selected strategies: Plastic → A, Glass → C, Metal → B.

Table 1. Data for simulation

Waste type	Strategy	Cost (EUR)	Revenue (EUR)	Net cost (EUR)
Plastic	A	0.45	54.00	-53.55
Glass	C	0.51	42.50	-41.99
Metal	B	0.48	66.50	-66.03

Source: Authors

The total net cost amounted to -161.56 EUR, indicating a positive financial effect of the system. The results demonstrate that the DSS model successfully integrates classification (Random Forest) and optimization in the selection of recycling strategies. Metal achieved the highest financial effect due to its high revenue and efficiency, while plastic and glass also produced significant positive results. These findings confirm that the proposed model can provide economically sustainable recommendations for waste management, with potential for extension to additional categories and criteria (e.g., environmental indicators, logistical constraints).

CONCLUSION

The simulation of the DSS model for waste recycling demonstrated that the integration of the Random Forest algorithm with the optimization model can provide economically sustainable and efficient recommendations for waste management. The results highlighted a significant advantage of the model, as revenues from the sale of recycled materials exceeded processing costs, which was confirmed in the cases of plastic, glass, and metal. The greatest financial effect was achieved with metal, while plastic and glass also produced positive outcomes.

These findings confirm that the DSS model can serve as a reliable decision support tool under real-world conditions, with the potential to be extended to a larger number of waste categories and diverse recycling strategies. Furthermore, the inclusion of environmental indicators (e.g., CO₂ emissions, material utilization rates) and logistical constraints (e.g., transportation, facility capacities) would enable the development of a multi-criteria model that balances both economic and ecological objectives.

Future research is recommended to expand the model to additional waste types and scenarios; apply advanced optimization techniques (evolutionary algorithms, stochastic optimization) and validate the model using real-world data from local communities. In this way, the DSS model can become the foundation for the development of intelligent waste

management systems that contribute to sustainable development and promote the principles of the circular economy.

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APPLICATION OF RANDOM FOREST IN THE ANALYSIS OF BIODIVERSITY CONSERVATION

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Abstract: This study demonstrates the application of the Random Forest algorithm in biodiversity analysis, focusing on the prediction of endangerment status for three migratory bird species in central Serbia: the turtle dove (*Streptopelia turtur*), the partridge (*Perdix perdix*), and the quail (*Coturnix coturnix*). By integrating biological, climatic, spatial, and anthropogenic data, the model achieved high predictive accuracy and identified habitat fragmentation and urbanization as the most critical risk factors. The results highlight the practical value of machine learning methods in supporting conservation strategies and decision-making processes for endangered species.

Keywords: Biodiversity conservation, Migratory birds, Random Forest algorithm, Habitat fragmentation, Urbanization impact, Climate change, Species risk prediction

INTRODUCTION

Biodiversity, or biological diversity, is defined as the variability of living organisms, including species diversity, genetic diversity within species, and ecosystem diversity (Alho, 2008; Taylor et al., 2020). This definition implies that the biodiversity of a particular region encompasses the collection of all genes, species, and ecosystems found within that area. The diversity of genes and their combinations in each region leads to morphological variations among individuals and populations within species, as well as taxonomic diversity of species within communities or ecosystems. These differences result in functional differentiation within specific species (Bartkowski, 2017), ultimately affecting the diversity of ecosystems themselves. The preservation of this biological diversity is of paramount importance for maintaining the health of our planet and the well-being of all organisms, including humans (Pault et al., 2020).

Consequently, biodiversity conservation represents one of the key challenges of contemporary society, as ecosystem degradation and species loss directly threaten the stability of natural systems and the quality of human life. Traditional methods of monitoring and analysing biodiversity, based on statistical techniques and field observations, often face limitations in processing complex and heterogeneous data. Modern approaches in computer science and artificial intelligence offer solutions to these challenges through the application of machine learning algorithms, which can model nonlinear relationships and integrating data from diverse sources.

Among machine learning algorithms, Random Forest stands out as a robust and interpretable method based on an ensemble of decision trees. Its application niches and ecology and biology has yielded significant results in predicting species distribution, classifying ecological niches, and identifying risk factors. It is particularly relevant in the context of forecasting the status of endangered species, where it enables the integration of climatic, geospatial, and biological data to assess extinction risk. In addition to high predictive accuracy, Random Forest provides interpretability through variable importance analysis, thereby informing researchers and decision-makers about the key ecological drivers of endangerment.

The aim of this paper is to present a methodological framework for applying the Random Forest algorithm in biodiversity analysis, with a particular focus on predicting endangered species. The study seeks to connect the theoretical foundations of the algorithm with practical implications for natural resource conservation, highlighting both the advantages and limitations of this approach. In doing so, it contributes to the development of interdisciplinary methods that bridge ecology, computer science, and environmental management.

MATERIAL AND METHODS

Random Forest represents one of the most widespread algorithms in the field of machine learning, especially intended for classification and regression tasks (Breiman, 2001, 1996). The essence of this approach is reflected in the construction of an ensemble of decision trees, where each tree independently analyses a subset of data, while the final decision is formed by aggregating the results of all models. This structure allows to reduce the variance of individual trees and obtain a more stable and reliable prediction.

One of the key advantages of the Random Forest algorithm is its resistance to the problem of overfitting, which makes it suitable for application to high-dimensional data sets with a large number of attributes (Breiman, 1998a). In addition, the algorithm shows high performance in situations where the volume of the sample is significant, and the characteristics are complex and non-linearly related to each other.

The method is based on the principle of ensemble learning, where a strong predictive model is obtained by combining several weaker classifiers. Random Forest uses the technique of random sampling of data and attributes (bootstrap and random feature selection), which ensures diversity among trees and increases the generalization of the model. The added value of the algorithm is reflected in the ability to assess the importance of variables, which allows researchers to identify the factors that contribute most to the prediction (Breiman, 1996b).

Although primarily used for classification and regression, Random Forest can also be adapted for clustering and anomaly detection tasks by integrating appropriate optimization criteria such as Akaike Information Criterion (AIC) or Bayesian Information Criterion (BIC). This further improves the accuracy and relevance of the results, especially in complex applications such as ecological modelling, endangered species prediction and biodiversity analysis.

RESULTS AND DISCUSSION

To demonstrate the practical application of the Random Forest algorithm in biodiversity analysis, a simulation was conducted on the prediction of the status of three endangered migratory bird species in central Serbia: the turtle dove (*Streptopelia turtur*), the partridge (*Perdix perdix*), and the quail (*Coturnix coturnix*). These species have in recent years faced a significant decline in population due to a combination of factors such as habitat loss, intensive agriculture, and climate change. The data used in the study included seasonal population size, available habitat area, average temperature and precipitation, as well as the intensity of urbanization in the immediate surroundings. The simulated data is presented in Table 1.

Table 1. Simulated data for the application of the Random Forest algorithm in biodiversity analysis

Loc	species	season	Pop	Habitat area (ha)	Fragmentation (plot/km ²)	°C	Rainfall (mm)	Urbanization (0-1)	Hunting pressure (0-1)
1	<i>Streptopelia turtur</i>	Spring	42	320	11	16.4	98	0.34	0.12
2	<i>Perdix perdix</i>	Summer	27	210	15	24.1	65	0.41	0.18
3	<i>Coturnix coturnix</i>	Autumn	35	280	9	18.7	112	0.29	0.10

Table 2. The result of simulation

Loc	Species	Season	Predicted status	Probability of endangerment	Probability of vulnerability	Probability of safety	Key risk factors
1	<i>Streptopelia turtur</i>	Spring	Endangerment	0.28	0.62	0.10	Fragmentation, urbanization
2	<i>Perdix perdix</i>	Summer	Vulnerability	0.71	0.23	0.06	Urbanization, hunting pressure, rainfall
3	<i>Coturnix coturnix</i>	Autumn	safety	0.11	0.31	0.58	Habitat area, lower fragmentation

The Random Forest model was trained on a set of 2.500 samples, using 500 decision trees with a random selection of attributes in each partition. The model classified species status into three categories: "threatened", "vulnerable" and "safe". The simulation results are shown in Table 2.

Performance evaluation demonstrated that the algorithm achieved an accuracy of 0.86, an F1-score of 0.81 for the "endangered" class, and a ROC-AUC value of 0.90, indicating high reliability in distinguishing species according to their level of risk. Variable importance analysis revealed that habitat fragmentation and the intensity of urbanization exert the greatest influence on status prediction, while climatic factors such as seasonal precipitation and average temperature contribute to a lesser extent. Higher fragmentation and urbanization increase the risk, whereas larger habitat area and lower fragmentation reduce the probability of endangerment.

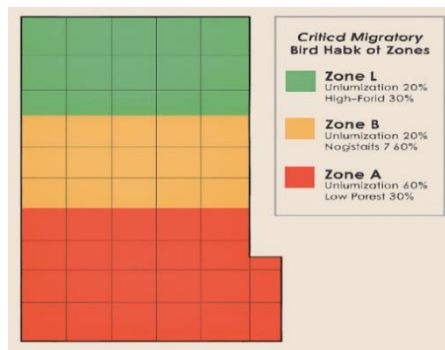


Figure 1. Visualization of the results through distribution maps

- **Red (Zone A):** High urbanization (>0.6), low forest cover ($<20\%$). These areas are most critical for species survival due to habitat loss and human pressure.
- **Orange (Zone B):** Moderate urbanization ($0.3-0.6$), moderate forest cover ($20-40\%$). Transitional risk, local conservation actions can make a strong difference.
- **Green (Zone C):** Low urbanization (<0.3), high forest cover ($>40\%$). Core refugia with the highest persistence potential.

Visualization of the results through distribution maps revealed that areas with high levels of urbanization and reduced forest cover are the most critical for the survival of the observed species. This example confirms that the Random Forest algorithm represents a robust and interpretable tool for biodiversity analysis, capable of integrating diverse types of data and providing reliable predictions regarding the status of endangered migratory birds. The obtained results highlight the practical value of the algorithm in supporting decision-making processes in the field of natural resource conservation and the planning of protective measures. A clear progression from high-risk (red) through medium (orange) to low-risk (green) zones. Prioritize mitigation (e.g., habitat restoration, reduction of disturbance) in red zones; strengthen protection and connectivity in green zones; target adaptive management in orange zones.

CONCLUSION

The findings of this study confirm that the Random Forest algorithm is an effective and interpretable method for biodiversity analysis, particularly in predicting the status of endangered migratory birds. By integrating biological, climatic, geospatial, and anthropogenic data, the model enabled reliable risk classification and identification of the key factors contributing to endangerment. High accuracy and the ability to analyse variable importance make this approach suitable for supporting decision-making in the field of natural resource conservation.

Visualization of results through spatial maps further highlighted critical zones where targeted protection measures are required, such as habitat restoration, regulation of urbanization, and control of hunting pressure. This methodological framework can be extended to other species and regions, thereby contributing to the development of interdisciplinary tools that connect ecology, computer science, and environmental management.

Future research should incorporate time-series data, high-resolution satellite imagery, and additional ecological indicators to enhance model precision and enable dynamic monitoring of biodiversity changes. This opens the way for the development of intelligent decision-support systems aimed at protecting endangered species and maintaining ecological balance.

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EFFECTS OF SOWING DENSITY ON GROWTH AND YIELD OF LEMON BALM (*Melissa officinalis* L.) MICROGREENS

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Abstract: Lemon balm (*Melissa officinalis* L.) is a perennial medicinal and aromatic plant traditionally used in the form of herbal teas, extracts, and fresh biomass. Although it has been extensively studied under conventional cultivation systems, information regarding its agronomic performance when grown as microgreens remains limited. The present study aimed to evaluate the effect of sowing density on germination dynamics, early growth, and fresh yield of lemon balm cultivated as microgreens under controlled environmental conditions. The experiment was conducted in 2025 under laboratory conditions using three sowing densities commonly applied in microgreen production: 3 g m⁻² (control, C), 6 g m⁻² (T1), and 9 g m⁻² (T2). Seeds were sown in plastic trays filled with a commercial peat-based substrate and grown under controlled temperature, relative humidity, and artificial lighting. Based on the thousand-seed weight (0.45 g) and seed use value determined according to ISTA rules (72%), the applied sowing densities corresponded to approximately 4.800, 9.600, and 14.400 plants m⁻², respectively. Germination, plant height, relative height increase, relative leaf area expansion, and fresh yield were monitored until harvest, which was performed 22 days after sowing at the stage of fully developed cotyledons and the onset of true leaf formation. Germination began on the 12th day after sowing and was completed by the 15th day in all treatments. Lower sowing density promoted earlier germination and faster early seedling development, whereas higher sowing density resulted in a greater number of established plants per unit area. Differences in plant height and relative leaf area were pronounced during the early growth stages but diminished by the time of harvest. Sowing density had a pronounced effect on fresh biomass yield, with the highest density (T2) achieving the greatest yield per unit area (approximately 90 g m⁻²) due to increased plant density, despite reduced individual plant weight. In contrast, the control treatment (C) produced heavier individual plants but resulted in the lowest total fresh yield (approximately 56 g m⁻²). The results indicate a clear density–yield trade-off in lemon balm microgreen production, suggesting that higher sowing density is more suitable for maximizing fresh biomass yield. This study provides new agronomic insights into the cultivation of *Melissa officinalis* as microgreens and contributes to the limited body of literature on medicinal and aromatic plants grown in this production form.

Keywords: Density, Germination dynamics, Early growth, Fresh yield

INTRODUCTION

Lemon balm (*Melissa officinalis* L.) is a perennial aromatic and medicinal plant belonging to the family Lamiaceae, traditionally used in the form of herbal teas, infusions, aqueous

and alcoholic extracts, as well as in the food, pharmaceutical, and cosmetic industries. The dried aerial parts of the plant, primarily the leaves, are most commonly utilized due to their characteristic lemon aroma and the presence of numerous bioactive compounds. In modern production systems, lemon balm is cultivated as an open-field or protected crop aimed at producing herbal raw materials or fresh biomass (Waheed et al., 2020). In addition to conventional cultivation systems, recent studies have highlighted the potential of lemon balm for cultivation under controlled conditions, including indoor and closed-environment systems, where its responses to light and other environmental factors have been investigated (Appolloni et al., 2021). In this context, *Melissa officinalis* L. has recently been considered a suitable species for microgreen production, opening new possibilities for its utilization at early growth stages, characterized by a short production cycle and a cultivation approach distinct from conventional systems (Newman et al., 2023). Microgreens represent a relatively new category of horticultural products, comprising young plants of vegetable, aromatic, and medicinal species grown from emergence until the stage of fully developed cotyledons and the appearance of the first true leaves. Owing to their short production cycle, limited space requirements, and suitability for controlled-environment cultivation, microgreens are increasingly recognized as an appropriate production system for urban and intensive agriculture, as well as a model system for studying the effects of agronomic factors on plant growth and yield (Partap et al., 2023). Previous research on microgreens has primarily focused on vegetable species, particularly those belonging to the family Brassicaceae, whereas aromatic and medicinal plants remain underrepresented in the scientific literature. Nevertheless, several studies have reported that species from the family Lamiaceae, including basil, mint, and lemon balm (*Melissa officinalis* L.), exhibit good adaptive potential for microgreen production, with pronounced differences in growth and yield depending on genotype and cultivation conditions (Partap et al., 2023; Di Gioia et al., 2023; Newman et al., 2023). Fresh yield is a key production parameter in microgreen cultivation, as it directly determines the economic viability of this production system. Previous studies have shown that microgreen yield varies considerably among species and is strongly influenced by sowing density, seed size, and the number of shoots per unit area. An optimal sowing density enables efficient space utilization while preventing excessive intra-specific competition, which may otherwise result in reduced individual plant biomass and overall yield (Gordanić et al., 2025). In aromatic plant species, sowing density plays an additional role by influencing plant physiology, growth intensity, and biomass accumulation efficiency within the very short growth period characteristic of microgreens (Xu et al., 2023). Although *Melissa officinalis* L. has been extensively studied as a perennial medicinal plant under conventional cultivation systems, information regarding its growth behavior and production characteristics at the microgreen stage remains limited. Existing literature has largely focused on the biochemical properties of mature plants or the effects of light on metabolism, whereas basic agronomic parameters, such as sowing density and its impact on microgreen yield, have not been sufficiently investigated. Therefore, there is a clear need for systematic research on the production aspects of lemon balm grown as microgreens, with particular emphasis on the effect of sowing density on yield performance. Understanding these relationships is essential for defining optimal production technologies and may contribute to the wider adoption of lemon balm in commercial microgreen production. The objective of this study was to evaluate the effect of three different sowing densities on the fresh yield of lemon balm (*Melissa officinalis* L.) microgreens in order to identify the optimal density that ensures maximum yield per unit area under controlled growing conditions.

MATERIAL AND METHODS

Seeds

The experiment was conducted using reproductive material (seeds) of lemon balm (*Melissa officinalis* L.) originating from the collection of the Institute for Medicinal Plant Research “Dr Josif Pančić”, Pančevo, Serbia (44°52'20.0" N; 20°42'04.7" E). The thousand-seed weight was 0.45 g, while the seed use value, determined in accordance with the ISTA rules (International Rules for Seed Testing), was 72%.

Experimental Design

The experiment was conducted in late March 2025 in the laboratory of the Department for Agricultural Research and Development, Belgrade, Serbia (44°49' N; 20°28' E), under controlled environmental conditions, to assess the effects of different sowing densities on germination dynamics and early growth of lemon balm (*Melissa officinalis* L.) cultivated as microgreens, up to the stage of fully developed cotyledons and the onset of the first true leaves. Three sowing density treatments commonly applied in microgreen production were evaluated: 6 g m⁻² (T1) and 9 g m⁻² (T2), while a standard sowing density of 3 g m⁻², according to the methodology of Stepanović et al. (2009), was used as the control (C). All treatments were arranged in four replicates. Based on the thousand-seed weight (0.45 g) and seed use value determined in accordance with the ISTA rules (72%), the applied sowing densities corresponded to approximately 4.800 plants m⁻² (C), 9.600 plants m⁻² (T1), and 14.400 plants m⁻² (T2). Plant density was not considered an experimental factor but was calculated as a derived parameter reflecting germination success and early seedling establishment under microgreen cultivation conditions. Sowing was performed in plastic trays (“Dno-Flex”) measuring 31×51 cm (surface area 0.15 m²), previously filled with a commercial peat-based substrate (“Plagron Grow Mix”). The substrate consisted of a mixture of white and black peat enriched with fibers and perlite, with a neutral reaction (pH H₂O 6-7), electrical conductivity (EC) ranging from 1.0 to 1.5 mS cm⁻¹, and a nutrient composition of NPK 12:14:24, including a potassium oxide (K₂O) content of 4.6%.

Growing Conditions

After sowing, the trays were placed under controlled environmental conditions to ensure optimal parameters for seed germination and seedling growth. Artificial lighting was provided using cool fluorescent tubes with a 12 h photoperiod. Relative air humidity in the growth chamber ranged between 60 and 70%. Air temperature was maintained between 20 and 24 °C, while substrate temperature was kept stable at 21 ± 2°C. Air temperature and relative humidity were monitored using a HAXO-8 data logger, whereas substrate temperature was measured using a Testo 110 thermometer (Gordanić et al., 2025).

Growth Measurements

During the germination and early growth phase of lemon balm, seed germination was evaluated daily during the first seven days following emergence, in accordance with the ISTA standard, using the following equation:

$$\text{Germination rate} = (\text{total number of seeds}) / (\text{number of germinated seeds}) \times 100$$

Subsequently, relative plant height increase was monitored following the method described by Radford (1967):

$$\text{Relative height increase} = (H_{\text{final}} - H_{\text{initial}}) / H_{\text{initial}} \times 100$$

Where:

H_{final} - plant height at the end of the measurement period (e.g., at the end of the experiment),

H_{initial} - initial plant height (e.g., at the start of the experiment or measurement).

In addition, relative leaf area increase was quantified using the Canopeo software, following the methodology developed by Patrignani et al. (2015).

Harvest and Yield Determination

Harvest was performed 22 days after sowing, at the stage characterized by fully developed and turgid cotyledons and the onset of true leaf formation. The number of plants per tray was recorded for each treatment. Seedlings were harvested by cutting at the substrate level using sterile cutting tools, and the collected biomass was immediately weighed. Fresh yield was determined using an analytical balance (KERN) and expressed on an area basis as g m⁻².

Statistical Analysis

Collected data were organized and preliminarily processed using Microsoft Excel. Statistical analysis was performed using one-way analysis of variance (ANOVA), and differences among treatment means were evaluated using Duncan's multiple range test at a significance level of $p < 0.05$. All statistical analyses were conducted using SPSS software.

RESULTS AND DISCUSSION

Germination Dynamics of lemon Balm Microgreens

Seed germination and emergence of lemon balm (*Melissa officinalis* L.) microgreens exhibited a delayed onset compared with many commonly cultivated microgreen species. Germination in all sowing density treatments began on the 12th day after sowing and was completed by the 15th day. This delayed germination behavior is characteristic of *Melissa officinalis* and has been associated with small seed size, lower initial metabolic activity, and specific physiological requirements for successful germination (Stepanović et al., 2009; Di Gioia et al., 2023).

The control treatment (3 g m⁻²) exhibited the earliest and most uniform germination response, with significantly higher germination values recorded during the initial germination phase (days 12 and 13) compared with higher sowing density treatments. In contrast, the highest sowing density (9 g m⁻²) showed a slightly slower initial response but reached the highest cumulative germination by day 15.

Table 1. Average seed germination per treatment (%)

Days after sowing	T1	T2	C
1-11	/	/	/
12	8.5 ± 1.2b	6.2 ± 0.9c	12.4 ± 1.5a
13	24.6 ± 3.1b	21.3 ± 2.7b	38.7 ± 4.2a
14	52.8 ± 4.9b	60.4 ± 5.6a	65.2 ± 5.1a
15	68.3 ± 5.7b	82.6 ± 6.4a	74.5 ± 6.0ab

* Values followed by the same lowercase letter within a row are not significantly different ($p < 0.05$)

These results indicate that lower seed density provided more favorable microenvironmental conditions for early germination, whereas higher density ensured a greater number of established seedlings per unit area, consistent with previous reports on microgreen establishment patterns (Di Gioia et al., 2023).

Plant Height Development

Average plant height measurements revealed distinct growth patterns during early development, followed by convergence among treatments at harvest. At 15 and 18 days after sowing, plants grown at the lowest sowing density exhibited significantly greater individual height compared with those grown at higher densities, reflecting reduced intra-specific competition for light, water, and nutrients.

Table 2. Average plant height per treatment (cm)

Days after sowing	T1	T2	C
15	0.82 ± 0.09b	0.65 ± 0.07c	1.10 ± 0.11a
18	1.95 ± 0.17b	1.82 ± 0.15b	2.24 ± 0.19a
20	2.95 ± 0.21a	3.02 ± 0.23a	3.05 ± 0.22a
22 (harvest)	3.80 ± 0.24a	3.88 ± 0.26a	3.75 ± 0.25a

*Values followed by the same lowercase letter within a row are not significantly different ($p < 0.05$)

By harvest (22 days after sowing), no statistically significant differences in plant height were observed, indicating that sowing density primarily influenced early growth dynamics rather than final plant height. Similar growth convergence has been reported for other microgreen species (Radford, 1967; Kyriacou et al., 2016).

Relative Increase in Plant Height

Relative plant height increases followed trends similar to absolute height values. During early growth, the control treatment exhibited the highest relative increase, while higher sowing densities showed slower relative growth.

Table 3. Average relative height increases per treatment (%)

Days after sowing	T1	T2	C
15	14.2b	11.6c	19.8a
18	38.4b	34.9b	46.7a
20	71.5a	73.2a	74.8a
22	100.0a	100.0a	100.0a

*Values followed by the same lowercase letter within a row are not significantly different ($p < 0.05$)

By harvest, relative height increases values converged across all treatments, confirming the compensatory growth capacity of lemon balm microgreens (Radford, 1967; Lee et al., 2017).

Relative Leaf Area Development

Relative leaf area expansion was significantly influenced by sowing density during early growth stages. Plants grown at lower density exhibited higher relative leaf area values, likely due to reduced competition and greater lateral expansion.

Table 4. Average relative increase in leaf area per treatment (%)

Days after sowing	T1	T2	C
15	18.4b	14.9c	29.6a
18	41.2b	38.5b	55.8a
20	62.9b	65.4ab	68.1a
22	100.0a	100.0a	100.0a

* Values followed by the same lowercase letter within a row are not significantly different ($p < 0.05$)

As growth progressed, differences diminished, and by harvest all treatments reached comparable relative leaf area values, consistent with canopy closure effects reported in previous studies (Patrignani et al., 2015; Wang et al., 2019).

Fresh Yield and Yield Components

Fresh yield parameters clearly demonstrated the dominant role of sowing density in determining lemon balm microgreen productivity.

Table 5. Fresh yield parameters per treatment (harvest at 22 DAS)

Treatment	Number of plants (m^{-2})	Plant weight (mg plant^{-1})	Fresh yield (g m^{-2})
T1	$118.4 \pm 8.6\text{b}$	$0.043 \pm 0.003\text{b}$	$72.4 \pm 4.8\text{b}$
T2	$154.6 \pm 11.9\text{a}$	$0.038 \pm 0.002\text{c}$	$89.6 \pm 6.3\text{a}$
C	$74.2 \pm 6.1\text{c}$	$0.052 \pm 0.004\text{a}$	$56.1 \pm 3.9\text{c}$

* Values followed by the same lowercase letter within a column are not significantly different ($p < 0.05$)

The control treatment produced the heaviest individual plants, whereas the highest sowing density achieved the greatest fresh yield due to a higher number of plants per unit area. This density yield trade-off confirms that total biomass production in microgreens is more strongly driven by plant density than by individual plant size (Di Gioia et al., 2023; Zhang et al., 2021).

CONCLUSION

This study showed that sowing density significantly affects germination dynamics and fresh yield of lemon balm (*Melissa officinalis* L.) grown as microgreens. Germination began on the 12th day after sowing and was completed by the 15th day in all treatments, with lower sowing density promoting earlier germination and faster early development.

However, differences in plant height and leaf area among treatments diminished by harvest 22 days after sowing.

Fresh yield was primarily determined by plant density, ranging from approximately 56 g m⁻² in the control treatment to 72 g m⁻² at the intermediate sowing density and reaching nearly 90 g m⁻² at the highest sowing density. The highest sowing density produced the greatest biomass per unit area despite reduced individual plant weight, while the control treatment yielded heavier individual plants but the lowest total yield. These results indicate a clear density-yield trade-off and suggest that higher sowing density is more suitable for maximizing fresh yield of lemon balm microgreens under controlled conditions.

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SMART AGRICULTURE - TECHNICAL AND ECONOMIC FACTORS OF DEVELOPMENT

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Abstract: The authors consider the key factors in the development of smart agriculture. These are technical and socio-economic factors. Technical factors are related to scientific and technical progress and innovations. In this connection, agriculture has undergone various historical developments, i.e. the evolution of agricultural techniques. It is a long historical path from manual tools to sophisticated smart technical systems. The development of smart agriculture, however, is strongly influenced by a complex set of economic and social factors, which determine the speed and extent of its implementation. There are many risks to this development path. The authors analyze in detail certain techniques and socio-economic factors of development. In the concluding remarks, they propose a multidisciplinary approach, an integral approach and a systemic approach in the development of this important, modern stage in the development of agriculture and rural development.

Keywords: Smart agriculture, Technical factors, Socio-economic factors, Risks, Conditions of development, Future of development

INTRODUCTION

Smart agriculture is a revolutionary concept that integrates cutting-edge technologies with traditional agricultural knowledge, creating a synergy that has the potential to transform global food production.

In addition, the development of smart agriculture depends on several key socio-economic factors: optimization of production factors; innovation models and commercialization; economic and agrarian policy of the state, investment in research and development, etc.

For the successful development of smart agriculture, it is necessary to integrate technical and economic factors. This integration requires a number of measures and actions of the state's economic policy, agrarian policy, education of young farmers about the possibilities of smart agriculture, development of the information system, etc.

MATERIAL AND METHODS

The material for this paper originates, first of all, from the master's thesis of the first author, which was defended at the Electrical Engineering of the FTN in Novi Sad, which is indicated in the list of references. There are also works published by authors from this field, as well as works by foreign authors.

The method of work is analytical (method of analysis and synthesis), historical method, comparative method, descriptive method, as well as other methods. The results of the research are given in the headings that follow in the paper.

HISTORICAL CONTEX AND EVOLUTION OF AGRICULTURAL TECHNIQUES

The first technological revolution was agriculture itself as the planned cultivation of plants and domestication of animals, which transformed nomadic hunter-gatherers into organized farmers. Since then, there has been a major evolution in agricultural technology from rudimentary hand tools to today's sophisticated smart systems.

The stages of evolution are:

Pre-industrial agricultural technologies, which used mechanical advances and animal power. Early civilizations (Mesopotamia, Egypt, China, America) developed specialized tools such as plows, irrigation systems, and warehouses. These innovations relied on human and animal energy. This energy paradigm would not change significantly until the Industrial Revolution began to transform agriculture in the 18th and 19th centuries;

Mechanical revolution in agriculture (18th-19th century). This period saw the introduction of iron ploughs, mechanical seed drills and early harvesting machines. The introduction of steam power marked a key change in the energy paradigm of agriculture. Steam-powered threshers and tractors at the end of the 19th century represented the first non-biological energy source used in large-scale agriculture, heralding the upcoming electric revolution (the transition from steam to internal combustion engines in agricultural machinery);

Electrification of rural areas (1900-1950). At the beginning of the 20th century, there was a gradual electrification of rural areas in developed countries, introducing the first electrical technologies in agriculture. This process started first in the USA, and then across Europe, although with different timelines and coverage. Electrical infrastructure created the foundations for modern agricultural practices and significantly improved labor productivity;

The Green Revolution: Chemical and Biological Innovations (1950-1970). This period was marked by the development of high-yielding crop varieties, synthetic fertilizers, pesticides, and expanded irrigation systems. These innovations led to dramatic increases in yields, but also increased dependence on irrigation, as well as growing concerns about environmental impact;

The emergence of precision agriculture (1980-1990) was followed by the emergence of several technologies: Global Positioning System (GPS satellites);

Geographic information systems (GIS - computer systems for storage, analysis and visualization of spatial data);

Variable rate technology (VRT - systems capable of changing the rates of application of seeds, fertilizers and pesticides based on field conditions);

Yield monitors (sensors and systems that measure and map crop yields during harvest) (Pejanović et al., 2025b);

Remote sensing (satellite and aerial photography systems that provide data on crop health, soil moisture and other variables in the field);

Precision agriculture primarily focused on site-specific crop management. This approach was a significant departure from the uniform methods of implementing the Green Revolution;

Digital agriculture and application of smart systems (2000-present). The beginning of the 21st century saw the emergence of precision agriculture and its evolution into digital agriculture. These included: Development of automated guidance systems (GPS guidance for tractors and equipment);

Wireless sensor networks (monitor conditions on the ground and transmit data wirelessly) (Pejanović, 2025);

Communication between machines (standards like ISOBUS allow machines and tractors to share data and coordinate operations);

Farm management information systems (software platforms integrate multiple data sources for comprehensive farm management);

Advances in remote sensing (satellite imagery and introduction of drone-based sensing systems).

The era of digital agriculture marked the increasing application of electrical engineering in agriculture (Pejanović, 2025).

Smart agriculture (2010-present). Its characteristics will be described in the following text.

TECHNICAL FACTORS OF SMART AGRICULTURE

The latest evolution in agricultural technology - differently called agriculture 4.0, smart agriculture or agriculture 5.0 - represents the convergence of digital agricultural systems with new technologies. Technical elements that enable the development of smart agriculture include:

Sensor technology - the development of hyperspectral sensors that enable precise monitoring of crop conditions, which is one of the foundations of smart agriculture. The

Internet of Things (IoT) represents interconnected sensor networks that monitor every aspect of agricultural production (Pejanović, 2025);

Drones and satellite technology - Space technology is used for crop monitoring and irrigation systems. These systems enable the collection of data on soil conditions, plant development and water needs over large areas with minimal human resources;

Artificial intelligence and machine learning - Neural networks and other machine learning systems enable the interpretation of a significant amount of data collected by sensors, and the making of precise decisions in resource management (Pejanović et al., 2025a). These include advanced algorithms that analyze agricultural data to recognize and predict patterns (Pejanović et al., 2024b);

Robotics and Automation - Autonomous and semi-autonomous systems perform numerous agricultural tasks;

Cloud and Edge Computing - Distributed processing capabilities that bring computing power to agricultural environments;

Blockchain Technology - Secure, transparent systems for agricultural supply chain management.

Starting from this, smart agriculture assumes a systemic approach that integrates these technologies in order to create adaptive, responsive agricultural production systems capable of optimizing the use of resources and achieving positive agricultural production results.

Smart agriculture implies the convergence of agricultural science and practice with advanced information, communication and control technologies. Scientists and practitioners use different terms - smart agriculture, agriculture 4.0, digital agriculture and precision agriculture - to describe aspects of this technological transformation.

Smart agriculture includes, therefore, the application of modern information and communication technologies (ICT) in agriculture in order to increase the quantity and quality of products while optimizing the necessary human work (Villa-Henricksen et al., 2020).

Key components of smart farming systems:

Sensor and monitoring systems (collect data on agricultural processes, environmental conditions and equipment performance using various sensor technologies) (Pejanović et al., 2025b);

Networks for data transmission and communication (these networks enable the transfer of data between sensors, processing systems and actuators) (Pejanović, 2025);

Data processing and analysis systems (these systems transform raw data into useful insights through various computational approaches);

Artificial intelligence and machine learning (advanced algorithms for pattern recognition and prediction) (Pejanović, 2024);

Decision-making and management systems (systems help decision-makers or make autonomous decisions based on processed data);

Actuation and management systems (these systems implement decisions by controlling agricultural equipment and infrastructure).

The interdisciplinary nature of smart agriculture stems from the above. The main disciplines contributing to smart agriculture include:

Agricultural sciences (crop and animal production, soil science, plant pathology); Electrical engineering (sensors, control, energy systems, communications); Computer science (data analysis, artificial intelligence, software development) (Pejanović et al., 2024a); Mechanical engineering (equipment design, robotics, fluid systems); Environmental science (ecosystem impact, sustainability assessment, climate interactions); Economics (cost-benefit analysis, investment planning, risk management); Social sciences (user adoption factors, workforce impacts, community effects). All this requires cooperation and joint work.

Smart agricultural technologies are applied in different agricultural sectors: Crop production - field crops: precision sowing, variable rate fertilization, automated harvesting; Viticulture: microclimate monitoring, selective harvesting, disease prediction; Orchards: automated pruning, selective harvesting, frost protection systems; Livestock production - dairy farming: automated milking systems, individual animal monitoring, nutrition optimization; livestock: precise feeding, health monitoring, environmental control; Aquaculture: water quality monitoring, automated feeding, production optimization; poultry: behavior monitoring, production monitoring, environmental control; Agriculture in a controlled environment - greenhouses (climate control, automated irrigation, additional lighting); Vertical farms (controlled environment, optimal use of resources); Indoor animal production (environmental monitoring and control systems).

There are many challenges in the application of smart agriculture. These challenges simultaneously drive numerous innovations. We will list the most significant challenges: Climate change (change in temperature patterns, change in precipitation patterns, extreme weather events); Lack of resources (water shortages, land constraints, energy challenges); Population growth and food security (increasing demand for food, yield differences and productivity challenges, food losses and waste); Labor challenges (adverse demographics, labor availability and costs, working conditions and safety); Requirements for environmental sustainability (emission of greenhouse gases, impacts on water quality, preservation of biodiversity, health and soil conservation); Compliance with regulations (regulatory frameworks, consumer expectations).

SOCIO-ECONOMIC FACTORS OF SMART AGRICULTURE

The development of smart agriculture does not depend only on technological innovations but is strongly influenced by a complex set of economic and social factors that determine the speed and scope of its implementation (Pejanović, 2013). There are many socio-

economic factors for the development of smart agriculture (Pejanović, 2013): Investment potential and financial instruments - we are talking about the availability of financial resources for investing in new technologies. Without adequate financial instruments and diversification of funding sources, farmers (especially those from less developed countries) face significant obstacles when implementing smart solutions; Economic sustainability and profitability - the application of modern technologies in agriculture requires significant initial investments in inputs (labor and equipment). At the same time, the key is to achieve an optimal relation between invested funds and achieved results; Market structures and access to markets - the existence of functional market structures enables farmers to access not only domestic but also international markets. In addition, the market influences the movement of food prices; In addition to economic factors, social development factors are also important (Pejanović, 2013). This includes demographic changes and age structure (Pejanović, 2013). Older farmers (whose share in rural areas population increases) are more difficult to adopt innovative technology than young ones. Education and knowledge transfer are very important. The social perception of agriculture as an activity and the willingness of the community to accept technological innovations significantly influence the pace at which smart agriculture develops. Namely, in many societies there is resistance to new technologies, partly due to traditional values, partly due to insufficient understanding of the advantages they bring; Development policies and strategies play a key role in creating a favorable environment for the development of smart agriculture. The Agriculture and Rural Development Strategy set the framework for the long-term development of the sector and can significantly speed up or slow down the introduction of smart technologies. Government incentives, including subsidies for the purchase of modern equipment, tax breaks and other financial instruments, can also significantly influence farmers' decisions to invest in smart technologies; Investing in research and development, as well as cooperation between scientific research institutions and agricultural producers, is an important factor in the development and adaptation of smart technologies to local conditions. The development of startup systems in the field of agriculture and support for incubators and science and technology parks can significantly contribute to innovations in this field; Technological prerequisites include digital infrastructure and availability of technologies. The development of digital infrastructure includes access to the Internet in rural areas, as well as equipment for precision agricultural machinery. Availability and affordability include not only the physical availability of equipment, but also the economic affordability that allows farmers of various economic capabilities to implement at least some level of smart solutions; The ecological dimension includes sustainable resource management, adaptation to climate change and renewable energy sources. Smart agriculture contributes to the sustainable management of natural resources through the optimization of the use of water, energy and other inputs. Along with the sustainable management of natural resources, the reduction of the use of pesticides, mineral fertilizers and other agrochemicals, and the ecological disposal of agricultural waste, smart agriculture is an important instrument in the fight against environmental degradation. Adaptation to climate change is possible through smart agriculture. Smart technologies enable better monitoring of weather conditions, more precise planning of agricultural activities and more efficient management of risks associated with climate change. The integration of renewable energy sources into agricultural production is an important aspect of smart agriculture (Pejanović, 2013).

CONCLUSION

The development of smart agriculture requires a multidisciplinary approach that integrates knowledge from the fields of agriculture, ecology, information technology and social sciences. Smart farming has real potential for more productive and sustainable agricultural production. This requires a holistic approach that takes into account all relevant socio-economic factors. The successful development of smart agriculture involves finding the optimal balance between economic goals and social needs, including food security, rural development and environmental protection. In addition to all that, education at all levels is important, as is the transfer of knowledge and skills. Technical-technological and socio-economic factors therefore play a decisive role in the development of smart agriculture, determining the pace and scope of its implementation. The successful development of smart agriculture requires an integrated approach that takes into account all relevant factors, from innovation and technology to economic incentives and financial instruments, through education, training and demographic trends, to the institutional framework. The future of smart agriculture depends on society's ability to create a favorable environment for its implementation, which implies adequate development policies and strategies, investments in education and research, development of digital infrastructure and incentives for farmers to adopt new technologies. Smart agriculture is not only a technological innovation, but a complex socio-economic phenomenon that requires a systemic approach and cooperation of all relevant actors, including the state, scientific research institutions, agricultural producers and society as a whole. Only through such an integrated approach is it possible to use the full potential of smart agriculture to achieve sustainable food production and rural development.

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BUCKWHEAT AS A HIGH-QUALITY RAW MATERIAL: NUTRITIONAL AND TECHNOLOGICAL PROPERTIES UNDER DIFFERENT STORAGE CONDITIONS

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Abstract: Buckwheat (*Fagopyrum esculentum*) is a pseudocereal with extremely beneficial nutritional composition. High content of quality proteins, dietary fibers, polyphenolic compounds (especially rutin), as well as the absence of gluten, makes it very common in human and animal nutrition since ancient times. Thanks to its low glycemic index, content of resistant starch and fiber, as well as the presence of bioactive compounds that affect enzymes involved in carbohydrate metabolism, buckwheat shows a favorable effect on the glycemic response. The aim of this work was to examine the chemical composition and content of biologically active compounds in buckwheat seeds, as well as the effects of storage conditions on changes in the quality of buckwheat. The results showed an extremely high content of gallic and *p*-coumaric acids, as well as epicatechin (91, 102.4 and 95.7 µg/g DW, respectively). Storage conditions did not significantly affect the content of gallic and *p*-coumaric acids, while the content of epicatechin decreased with longer storage time. Also, the content of total phenols, as well as antioxidant activity decreased with increasing storage time compared to the native sample. The results of this research contribute to the promotion of buckwheat and buckwheat flour as an extremely important raw material and the possibility of its application in the modern food industry.

Keywords: Buckwheat, Nutrients, Polyphenols, Antioxidants, Storage conditions, Functional food

INTRODUCTION

Buckwheat (*Fagopyrum esculentum*), a traditional annual pseudocereal, is valued for the high nutritional quality of its seeds used in human and animal diets. It does not require special growing conditions, and due to its short growing season, it is often grown as a cover crop after early spring crops (Jha et al., 2024). Buckwheat seeds are usually consumed as cereal after removing the husk and processed into flour. Buckwheat flour is used as raw material to make buckwheat-enriched food products such as bread, noodles, pasta, cakes, biscuits, and some valuable fermented products like wine, beer, and vinegar (Suzuki et al., 2020). The leaves of buckwheat can also be used as a tea and the flowers provide an excellent source of honey production due to their attractive colour and texture. During its flowering phase, it can produce up to 2000 flowers per plant, very rich in nectar. The grains

have an exceptionally beneficial nutritional profile, as their proteins include all essential amino acids necessary for human health. Moreover, the uniqueness of buckwheat stems from its complex biochemical composition - high contents of phenolic acids, bioflavonoids, especially rutin, minerals, vitamins, as well as dietary fibres. The lack of the allergenic protein gluten, makes it ideal for individuals with celiac disease as well as those with non-celiac gluten sensitivity (Salejda et al., 2022; Pisinov et al., 2024). Furthermore, an increasing body of scientific evidence highlights the multiple health-promoting effects of buckwheat, particularly its role in glycemic regulation, lipid metabolism, and the maintenance of digestive health.

Due to its favourable nutritional profile and bioactive compound content, it has also been associated with the prevention and mitigation of various chronic diseases, particularly cardiovascular disorders, hypertension, and obesity (Huda et al., 2021).

Recent research on buckwheat, both *in vivo* and *in vitro*, confirms its potential health benefits, including antitumor, anti-inflammatory, antioxidant, and hepatoprotective effects (Huda et al., 2021; Zhu, 2016). Buckwheat's bioactive components may help prevent several illnesses, including diabetes, high blood pressure, cancer, glycemic disorders, and more (Huda et al., 2021). It is a crop recognized for its exceptional nutritional profile and high concentration of bioactive compounds, which contribute to its functional and health-promoting properties (Wieslander et al., 2020).

Due to its high content of polyphenolic compounds that exhibit antioxidant activity, the use of buckwheat as an additive in bakery products is widespread. In addition to its use in the production of bread and pastries, buckwheat flour can be processed into various non-bakery products, such as noodles or pasta (Bojňanská et al., 2022).

In recent decades, buckwheat has also found application in the meat industry. Thanks to its water-binding properties, adding a small amount of buckwheat flour to semi-smoked sausage samples increases the moisture-binding capacity by 1.1-1.8%. Also, introducing hydrated buckwheat flour into minced meat up to 6% of the mass of raw meat raw material has a positive effect on the physicochemical, functional-technological, structural-mechanical and organoleptic parameters of semi-smoked sausages (Yessengazyeva et al., 2023).

In order to be used throughout the year, buckwheat must be adequately stored, which is one of the most important segments in the production chain, as it directly affects its quality, safety and economic value. Buckwheat, as a food raw material, remains subject to numerous biological, physical and chemical changes after harvest that can lead to spoilage, weight loss and a decrease in nutritional value. Therefore, its proper preparation and storage are considered a key step in ensuring stable and safe supplies for the needs of various users of this grain (Jose and Selvan, 2024). Like other grains, buckwheat can be sensitive to moisture, temperature, and attack by pests and diseases during storage.

This research focused on evaluating the nutritional properties, antioxidant potential, and biochemical profile of buckwheat. A significant aspect of the study involves exploring the changes in color and nutritional value of buckwheat during various storage durations, with the purpose of incorporating buckwheat into the development of functional foods.

MATERIAL AND METHODS

Buckwheat variety Novosadska was used for examination of nutrition and biochemical composition, as well as influence of storage conditions. Buckwheat was harvested at the moment of technological maturity of the seeds, and 2 kg of raw material was equally divided into eight samples. Six samples were stored for 3, 6, and 9 months in a drying oven at a temperature of 40 ± 2 °C with controlled thermoregulation and a relative humidity of 50%. After each storage period, samples were ground in a laboratory mill and stored in a refrigerator until analysis. All chemicals, reagents, and standard solutions used in the experiments were of minimum purity p.a. or higher. The chemical and nutritional properties of buckwheat were determined using standard international methods:

- 1) moisture content was determined gravimetrically, according to ISO 712 (2009),
- 2) total protein content, according to ISO 20483 (2013),
- 3) total lipid content according to NMKL 160 (1998),
- 4) total carbohydrate content according to AOAC 986.25 (1988),
- 5) starch content according to ISO 10520 (1997),
- 6) β -glucan (dietary fiber) content according to AOAC 995.16 (1995).

Extraction of buckwheat flour was performed according to a previously optimized method (Đurović et al., 2018). Total phenol content (TPC), ferric reducing/antioxidant power (FRAP), and radical-scavenging activity (DPPH) were determined spectrophotometrically, and the polyphenol profile was determined by reverse-phase liquid chromatography (HPLC), all according to a previously established method (Pisinov et al., 2024). For each parameter, analyses were conducted in triplicate and results were expressed as mean value $\pm$ SD.

RESULTS AND DISCUSSION

The results of the chemical and nutritional properties of buckwheat are shown in Table 1.

Table 1. Influence of storage period on chemical and nutritional properties of buckwheat variety Novosadska

Parameters, % (w/w)	Storage period			
	Freshly harvested grains	3 months	6 months	9 months
Moisture content	10.21 ± 0.006^d	9.09 ± 0.020^c	7.89 ± 0.066^b	6.02 ± 0.021^a
Total protein content	13.46 ± 0.344^b	12.62 ± 0.590^{ab}	12.25 ± 0.336^a	11.57 ± 0.448^a
Total lipid content	3.44 ± 0.152^b	2.99 ± 0.303^{ab}	2.64 ± 0.235^a	2.99 ± 0.050^{ab}
Carbohydrates content	81.13 ± 0.510^a	82.38 ± 0.676^{ab}	83.17 ± 0.465^b	83.48 ± 0.370^b
Strach content	62.55 ± 0.105^c	49.12 ± 0.315^a	47.67 ± 0.737^a	52.12 ± 1.342^b
β-glucan content	0.050 ± 0.0013^b	0.030 ± 0.0012^a	0.100 ± 0.0028^c	0.120 ± 0.0027^d

^{a,b,c,d} Means within the same row with different superscripts differ significantly ($p < 0.05$); nd -not detected; d.w. - dry weight

There was a significant difference ($p < 0.05$) in moisture content across all treatments. Total protein, total lipid, and carbohydrate content showed significant differences at 6 months, although this was not the case thereafter. Freshly harvested seeds exhibited the highest levels of moisture, total protein, and total lipid, while after 9 months, they decreased by 41, 14, and 23%, respectively. In contrast, carbohydrate content increased to its highest level in 9 months, increasing by 3% from freshly harvested seeds. Nutritional parameters of buckwheat flour changed over time, with a significant decrease ($p < 0.05$) in starch and an increase in β -glucan content. Statistically significant differences in β -glucan were noted across treatments, while differences in starch were significant at 3 months and continued thereafter. Our results on the Novosadska variety align with Dapčević et al. (2011), showing moisture, protein, and lipid contents of approximately 9.76, 13.40, and 3.08%, respectively

Antioxidant activity of buckwheat analyzed by conducting TPC, FRAP, and DPPH assays is shown in Table 2. Storage period led to significant decreases in TPC, FRAP, and DPPH. Compared to freshly harvested grain, which had the highest TPC and FRAP, the lowest values were recorded after 9 months, showing a 1.3- and 2.9-fold decrease, respectively. The highest DPPH value was noted after 3 months, with a 2.4-fold decrease by 9 months.

Table 2. Influence of storage period on antioxidant activity of buckwheat variety Novosadska, by three different assays

Parameters	Storage period			
	Freshly harvested grains	3 months	6 months	9 months
TPC, mg GAE/g d.w.	7.28 $\pm$ 0.194 ^c	6.97 $\pm$ 0.115 ^c	6.04 $\pm$ 0.121 ^b	5.57 $\pm$ 0.122 ^a
DPPH, μ mol TE/g d.w.	19.47 $\pm$ 0.907 ^c	19.66 $\pm$ 0.333 ^c	25.32 $\pm$ 0.445 ^b	22.20 $\pm$ 0.440 ^a
FRAP, μ mol Fe ²⁺ /g d.w.	63.45 $\pm$ 1.520 ^d	28.68 $\pm$ 0.476 ^c	2.64 $\pm$ 0.235 ^a	2.99 $\pm$ 0.050 ^{ab}

^{a,b,c,d} Means within the same row with different superscripts differ significantly ($p < 0.05$); nd -not detected; d.w. - dry weight

In the Novosadska variety of buckwheat, 15 polyphenolic compounds, nine polyphenolic acids, and six bioflavonoids were examined (Table 3). An example of a chromatogram of a mixed standard of examined polyphenolic compounds, with a concentration of 200 μ g/ml, monitored at two wavelengths of 280 nm and 325 nm, is shown in Figure 1.

Only one compound, hesperetic acid, was not detected in any of the samples. In all samples, p-coumaric acid was the most abundant, followed by gallic and trans-cinnamic acid, and storage period did not lead to statistically significant changes in their content. A significant decrease in chlorogenic acid content was observed during storage ($p < 0.05$) up to the sixth month, and thereafter there were no statistically significant losses. Changes in dihydrocaffeic and phloretinic acids were also significant but showed irregular patterns. Among bioflavonoids, daidzein, quercetin, and naringin increased significantly during storage, while epicatechin decreased significantly. There were no significant changes for catechin or naringenin.

Table 3. Influence of storage period on polyphenole profile of buckwheat variety Novosadska

Parameters, µg/g d.w.	Storage period			
	Freshly harvested grains	3 months	6 months	9 months
Gallic acid	91.0 ± 8.44	92.7 ± 6.97	94.1 ± 6.88	93.6 ± 7.53
Dihydrocaffeic acid	18.7 ± 1.93 ^b	11.5 ± 1.16 ^a	19.1 ± 1.95 ^b	15.5 ± 1.52 ^{ab}
Chlorogenic acid	14.4 ± 1.29 ^c	11.1 ± 1.10 ^b	7.6 ± 0.74 ^a	7.1 ± 0.72 ^a
Caffeic acid	38.2 ± 3.83	37.6 ± 3.97	39.2 ± 3.78	38.3 ± 3.87
Phloretic acid	25.8 ± 2.44 ^a	46.5 ± 4.11 ^b	31.4 ± 3.04 ^a	29.1 ± 2.65 ^a
p-Coumaric acid	102.4 ± 7.52	101.9 ± 7.57	97.8 ± 6.14	95.9 ± 6.90
Ferulic acid	56.5 ± 3.79	57.0 ± 3.56	57.4 ± 4.00	56.5 ± 3.80
Hesperetic acid	nd	nd	nd	nd
trans-Cinnamic acid	90.0 ± 4.76	89.9 ± 4.53	89.5 ± 4.27	87.9 ± 4.60
Catechin	49.1 ± 4.12	52.2 ± 4.28	49.9 ± 4.12	49.3 ± 4.20
Epicatechin	95.7 ± 7.87 ^c	78.5 ± 6.31 ^b	77.0 ± 6.46 ^b	59.8 ± 5.08 ^a
Daidzein	57.0 ± 4.25 ^a	59.3 ± 4.25 ^{ab}	56.1 ± 3.84 ^a	69.3 ± 4.98 ^b
Quercetin	9.8 ± 0.93 ^a	12.5 ± 1.27 ^{ab}	16.6 ± 1.69 ^b	47.1 ± 3.95 ^c
Naringin	nd	42.7 ± 2.91 ^a	54.9 ± 4.22 ^b	51.9 ± 3.70 ^b
Naringenin	38.4 ± 2.78	37.8 ± 2.33	38.7 ± 2.24	38.3 ± 2.33

^{a,b,c} Means within the same row with different superscripts differ significantly (p<0.05); nd -not detected; d.w. - dry weight

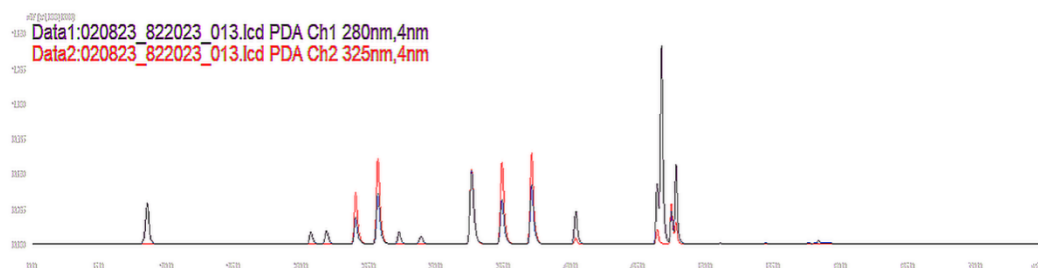


Figure 1. Chromatogram of a mixed standard of 15 polyphenolic compounds, with a concentration of 200 µg/ml, monitored at two wavelengths of 280 nm and 325 nm. The order of polyphenolic compounds is as follows: Gallic acid, Catechin, Dihydrocaffeic acid, Chlorogenic acid, Caffeic acid, Epicatechin, Phloretic acid, p-Coumaric acid, Ferulic acid, Hesperetic acid, Naringin, Daidzein, trans Cinnamic acid, Quercetin and Naringenin.

To the best of the author's knowledge, dihydrocaffeic and phloretinic acid, as well as daidzein, naringin, and naringenin, have been quantified for the first time in buckwheat flour of Novosadska variety, although there are a large number of studies in which several dozen different polyphenolic compounds were detected, both in different buckwheat varieties and in different parts of the plant (grain, stem, leaf), but also in products such as pollen and honey obtained from buckwheat (Kiprovski et al., 2015; Nešović et al., 2021; Yang et al., 2022). Furthermore, the research findings showed that storage does not lead to statistically significant changes in most of the parameters examined. This insight may be useful for the promotion and popularization of this variety, both among producers and consumers.

CONCLUSION

Buckwheat (*Fagopyrum esculentum*) is recognized as a highly valuable raw material for the formulation of functional foods, attributed to its favorable nutritional profile, significant content of bioactive compounds, and absence of gluten. Its diverse applications encompass a wide array of products, including gluten-free baked goods, fermented beverages, instant porridge, and energy bars. The advancement of novel processing technologies, alongside the synergistic combination of buckwheat with other natural ingredients, further enhances its applicability within the modern food industry.

In light of the growing consumer demand for natural and health-oriented food products, buckwheat holds considerable promise as a key ingredient in the development of functional foods in the forthcoming decades. Its unique attributes position it favorably within the health food sector, suggesting its potential to significantly impact dietary habits and nutritional patterns.

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THE IMPORTANCE OF AGROBIODIVERSITY FOR AGROECONOMY UNDER THE INFLUENCE OF CLIMATE CHANGE

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Abstract: Food and its production represent a fundamental link between human society and its environment. This direct and multiple connection reflects a multitude of environmental influences and conditions, making agriculture one of the most significant, complex, and sensitive socio-economic activities. In this primary economic activity, in the millennia-long history of humanity, the basic goal is to provide a sufficient quantity of quality food for the population, that is to say, the optimal ratio of invested funds and produced profit. In order to meet economic criteria, the diversity of plant and animal species was significantly reduced in the 20th and early 21st centuries, with incalculable consequences for agrobiodiversity and the systemic functioning of the agroecology. The aim of this paper is to highlight the importance of agrobiodiversity for a sustainable agroecology in the face of evident climate change at regional and global levels.

Keywords: Agrobiodiversity, Agriculture, Agroecology, Climate

INTRODUCTION

Climate represents a complex system of conditions and influences in which a relatively stable relationship between water, land and air functions in one region, which is to say, it is the whole of the balanced influence of energy, water and carbon cycles. (Vuković et al., 2024). Climate denotes the totality of meteorological factors which mark a relatively stable state of weather phenomena within a region for a long period of time. Climatic conditions represent one of the most significant natural sources for economic and overall social development because they provide relatively stable natural conditions for the growth of economy. Climate directs the entire human activity, from the production of food and clothing, over the construction of appropriate shelters/settlements, to large drainage and irrigation infrastructural projects. The climate of a certain region is influenced by multiple factors, such as astronomical ones (rotation of the Earth and activity of the Sun), geographical (relation between land and sea, latitude) and meteorological (heat, precipitation).

Even in the oldest periods of human society's development, groups and communities either adapted to climatic conditions or migrated under the influence of (un) favorable conditions, both in order to ensure the desired stable and suitable conditions for economic activity. At the same time, society itself, with its economic and overall cultural activity, significantly influenced the intensification or migration of climate manifestations. This was present in several ancient civilizations, and particularly in the last and present century, when CO₂

emissions reached levels that rapidly changed global climate conditions and caused an ecological crisis.

This notwithstanding, social organization and technology are capable of directing a community so as to survive and achieve some comparative advantages. For most of history, climate changes occurred through natural astronomical, meteorological, and accidental changes while humans had few organizational and technological resources to conform with or adapt to these changes. They opposed the climatic changes by becoming organized (by launching large melioration infrastructural projects as far back as in the old century) or by migrating to more convenient regions. In the last two centuries, there has been an unprecedented global impact of human economic activity on global climate changes along with a simultaneous inconceivable increase in technological and organizational capacities of mankind.

At the very early stages of its development, agriculture aimed at ensuring an adequate selection of plant and animal species that would provide a stable quantity of population quality food. As a rule, the process proceeded in the direction of selection and reduction of species for agricultural production, which resulted in agrobiodiversity being gradually lessened. Only in recent decades has there grown an awareness of the importance of old but presently commercially marginalized plants and animal species and the activity on their preservation.

Until the very seventies of the last century (Giddens, 2010), there was a widespread scientific belief that the potential of man and society to use science, technology and organization to gain power over climate is almost unlimited. At the same time, indisputable historical and archeological proofs came to light, indicating that many social communities either vanished or faced a significant and long-term recession right under the influence of climatic changes. The reliance on monocultures and the reduction of agricultural species proved to be unsustainable due to the lack of agro-economic adaptation to climatic changes.

On account of considerable economic difficulties in the fields of energy and agriculture, ecologists and economists started intensifying scientific activity on mapping and defining climate changes which became the ones of the basic features of ecological crisis. In contemporary conditions, the existence of climatic changes is not questioned in science (Luković and Burić, 2023) but are raised the issues of slowing down these changes and mastering them, as well as establishing the adaptation to them. The consequences of climate change are global as they affect the entire planetary living world and, in particular, global agricultural and economic activity.

Biodiversity as a Development Factor

In relation to climatic changes, the socio-economic scenario (Vuković et al., 2024) reflects on the number of inhabitants, use of resources and land, average income and the level of inequality in society, while the richness of flora and fauna is considered only within the framework of the sustainability of regional or global economies. However, if social development is viewed inclusively and integrally, the protection and preservation of biodiversity is an inseparable and indispensable component.

Along with climate, the richness and diversity of the plant world is an indicator of the quality and preservation of soil and thus, as a factor of development, it directly affects a number of economic branches, such as agriculture, forestry, the construction industry, etc. Agrobiodiversity consists of the diversity of cultivated plant and animal species which are grown in an organized manner in agricultural production to ensure the population's nutrition with foods of plant and animal origin.

Economic laws (Stern, 2007) and profit-oriented economy require agricultural specialization and monoculture production so that the highest possible yields can be ensured. Whether it is plant or animal production, the need for the largest possible quantity of food is achieved by selecting those agricultural and livestock species which will, with the lowest investments, result in the highest yields, while the production of those species which in certain conditions give poorer yield is either suppressed or demotivated. In this way production costs are reduced, yields increased, market dominance ensured, and the prospects to control the entire process enhanced. Apart from intensive agricultural production, other causes of agrobiodiversity loss are also the use of plants and animals for industrial and energy purposes (soy, corn, rapeseed), clothing production (linen and cotton) and state subsidies for certain high-yielding species.

In modern social ecology there is a prediction about the protection of agrobiodiversity which aims to scientifically understand and anticipate the difficulties related to climatic changes and the loss of plant and animal species. Thus, according Cifrić (2012) these are the following challenges:

- 1) expansion of property rights and restriction of access to seed material by "intellectual property" and patenting that creates monopoly rights (GMOs),
- 2) biomass cultivation for energy purposes which quadrupled between 2000 and 2005 and
- 3) climate change (global temperature rise, extreme weather conditions).

The first challenge of agrobiodiversity is primarily related to GM agriculture, that is, to such production in which "genetically engineered seeds" (GMO) are used with an aim to obtain higher yields and greater resistance to diseases and pests. GM agriculture itself is a very controversial topic in the scientific and professional public, both in the ecological and health aspects, as well as in the economic and social aspects. In the beginning, perhaps the least problematic issue was the economic aspect of GM agriculture, as cheaper agricultural products and their larger quantities are provided in this way. Cifrić (2012) explains the questionability of the economic aspect by taking the example of Argentina, where the initial economic success of increasing the quantity of products was quickly called into question by the devastating consequences in the form of land degradation, a decrease in yields of up to 15%, the collapse of agribusiness in smaller areas, and the growth of unemployment, deforestation in order to obtain arable land, the appearance of more resistant weeds and harmful insects. (Cifrić, 2012).

There is much more disagreement about the environmental and health effects of agriculture which uses GMOs. While some (Jošt and Cox, 2003) emphasize anemia, malnutrition, premature sexual maturity in children, autoimmune diseases and autism, others deny the direct connection between cultivation and the use of GMOs in food and increasing presence of degenerative health problems. In an ecological sense, genetically modified organisms and their mass use in food do not meet the basic principles of sustainability, namely

precaution and risk assessment. GMO supporters do not pay due attention to research work on possible harmful aspects of these foods, which prevents a proactive approach to take place in a number of economic and other social activities. As for the social aspect, the most significant problem is the insufficient transparency of GMO producers and the monopolization of intellectual property. Owners of monopolistic GMO seed material determine the conditions of use and prices, while the producers themselves remain passive "contractors" without the possibility, for example, of harvesting seeds from their plots. Due to all the current and potential risks and problems, it is necessary to involve more intensively independent scientific institutions in transparent research on all aspects of endangering agrobiodiversity through GM agriculture.

Cultivating biomass and using it in the production of renewable energy opens up a significant opportunity to overcome the limitations of non-renewable energy sources. The cultivation of corn and soybeans to produce biofuels used in the internal combustion engines of individual vehicles is above all unethical. As long as there are hungry people on the planet, it is thoroughly against morality to process and use huge amounts of food for the luxury of individual mobility. However, waste from agriculture (straw, corn stalks, waste from pruning), waste from animal husbandry (manure) and residues from wood processing (bark, branches, sawdust) represent biomass with considerable potential for improving agrobiodiversity, in a way that encourages the cultivation of the largest possible number of plants which can contribute to energy sustainability and diversification. On the contrary, the cultivation of a limited and smaller number of wood species with a rapid increase in wood mass can have immeasurable ecological consequences in the case of mass infestation by pests, or in the case of climate changes that would affect their dying out. Attentive, systematic and scientifically inclusive treatment of all aspects of biomass cultivation, along with scientific prediction of possible climate impacts, could have economically profitable effects, without jeopardizing the abundance of plant and animal species along the way.

Climate changes are reflected in the increase in global temperature, increase or decrease in the amount of precipitation, the frequency of extreme weather conditions (long dry periods, floods), the reduction of the global snow and ice cover, the rise in sea level and the increase in economic damages, which are due to the synergistic effect of the mentioned phenomena, and especially due to extreme weather conditions. Although climate changes are not an unambiguously defined global environmental problem, their significance from security and environmental aspects is more than obvious. Apart from this, it has been made evident that deforestation and soil desertification only contribute to more serious consequences for climatic changes. In terms of consequences for the global climate, deforestation of indigenous tropical forests is of particularly devastating outcomes. The loss of these forests may not have directly affected agriculture. Even more, its scale may have been broadened in terms of new arable areas. Yet, the indirect consequences are certainly fatal in ecological and economic sense. We should not forget that the loss of biodiversity of numerous plants and animal organisms entails the direct absence of potential medical, genetic and biological benefits for the survival of mankind on the earth.

Agriculture and Agrobiodiversity

Traditional agricultural production is based on solar energy, biomass, animals and human labor, but in terms of yields, it is multiple less compared to modern food production.

Modern agriculture is based on significant and increasing inputs in the form of artificial fertilizers, pesticides, irrigation and mechanization, all of which are directly related to the availability of non-renewable fossil fuels (Harris, 2009). Since deforestation results in a series of grave consequences for the wider ecosystem in the form of soil erosion and degradation, modern agriculture can no longer rely on new arable land. Illustrating modern agriculture, (Cifrić, 2012) discloses that in Germany in the second half of the 20th century 75% of agricultural and garden grown species disappeared, and that out of 35 known breeds of cattle only 5 are commercially raised. Whereas the elementary economic principle of ensuring the survival and growth of only those species providing the highest yields is applied to agriculture, the ecological principle of diversity, the health principle of resistance, and even the economic principle of diversification is ignored.

In order to enable the sustainability of agriculture in modern conditions, that is, to ensure a sufficient amount of quality food for the population, along with ecological protection of the environment, it is necessary to observe agriculture through an interdisciplinary approach. In other words, it is required the maximum use of renewable resources (waste from the harvest plowed, and manure used as an alternative source of energy); the use of crop rotation along with the necessary fallow land; simultaneous cultivation of several agricultural crops on the same plot to prevent the effects of pests and diseases, as well as to obtain higher yields (legumes and corn); more efficient irrigation methods; minimal plowing techniques, etc.

On a global scale, agricultural production provides sufficient food which is sufficient for the adequate nutrition of every individual in the world (Harris, 2009). In this economic activity as well, the core of the problem lies in inadequate distribution along with the dominance of profit. However, although the quality of nutrition of the population is globally improving, the imbalance is caused by the mismatch between production and distribution. Harris, for example, illustrates this discrepancy by offering some exact data: half of the world's arable land is used for the production of a limited number of cereals while the other half is used for all other crops. To ensure a preferred and dominant meat diet, for example, in the USA three quarters of grain is used for livestock feeding (Harris, 2009).

The reduction of the diversity of cultivated plant and animal species represents a direct reduction of the actual and projected adaptive capacities of an economy. A small number of species of one crop may not make a sufficient biogenetic potential to adapt to current and future climatic changes. A higher level of diversity in agro-economy allows for flexibility in planning, control and community organization for upcoming climate change.

Adaptation, Mitigation and Agroecology

The contemporary global community has the technological and organizational capacities to oppose climatic changes through mitigation or adaptation. Mitigation implies lessening climatic changes impact by reducing the amount of greenhouse gas emissions in order to slow down and prevent the warming of the planet and to stabilize the climate (Vuković et al., 2024). Adaptation represents adjusting to climate changes with the goal of taking measures for sustainable development in climate-changed and unstable conditions, that is to say, the goal of adaptation is to provide sufficient food, preserve the environment and enable stable living conditions. Mitigation is globally oriented and requires international

agreements and voluntary global standardization. Adaptation requires local action and national regulation. However, there is also an overlap of mitigation and adaptation in the cases of use of renewable energy sources, rational consumption of energy, water and soil, reduction of CO₂ emissions, education related to the protection and improvement of the environment, interdisciplinary and inclusive action of various disciplines. It is precisely the fact that these two processes complement and combine in a complete accordance with the motto of sustainable development: "Think globally, act locally"!

Neither mitigation nor adaptation is feasible without scientific and technical means to enable the acquisition of knowledge about the risks, existence and the nature of climate change. Based on such insights, it is possible to approach the planning and organization for mitigation and adaptation processes to take place. While mitigation is long-term and requires complicated consultation processes, and its control is slow and ineffective, adaptation may be performed even in smaller regional areas. Due to this nature of mitigation and adaptation, the study of system vulnerability has become an initial area of research and action.

Vulnerability of social (sub)systems, and especially the economic ones, are basic areas of research in the field of climate changes. Vulnerability can be mitigated by reducing sensitivity and exposure, and by increasing the capacity for adaptation (Vuković et al., 2024). Reducing sensitivity implies enabling different sectors to endure the growing effects of climate changes without major negative consequences. Exposure reduction is the avoidance of the bad impact on certain systems exposed to climatic changes. An increase in adaptive capacity implies such performances of the system by which it adapts itself to changed climatic conditions, that is to say, the system is to become more resistant to climate changes.

In the thematic framework of this paper, increasing the adaptive capacity of agrosystems implies the existence of organizational and scientific-technological processes which will enable the smooth functioning of food production. In this sense, the strengthening of the Global Fund for Crop Diversity (www.thwgef.org) which puts the protection of agrobiodiversity in direct correlation with climate changes, population health status and economic development. In this framework, the opening of new "seed banks" and national or regional, protected agricultural areas with commercially less profitable plant and animal species represent concrete measures for the protection of overall agrobiodiversity. There are around 1.700 gene banks worldwide (forbs.n1info.rs/inovacije from 9/28/2024). Such a "seed bank" in Svalbard, Norway (Svalbard Global Seed Vault) owns and stores 1,300,000 samples from all over the world. Preservation of agrobiodiversity is the basis for the reduction of agricultural production's sensitivity. A greater number of plant and animal species represent a reservoir of genetic diversity that may in the future preserve its adaptive capacity of food production or increase it.

CONCLUSION

Climate change and the protection of agrobiodiversity are interrelated and conditioned phenomena which considerably affect agriculture, and hence the overall economy. Profit-oriented agriculture strives to provide as much food as possible with as few production costs as possible. For this reason, a whole series of processes is carried out, from the

selection and reduction of species to genetically modified organisms, which all together result in the reduction of plant and animal species grown for food. In the food production industry, climate change has double effects. On the one hand, climate changes affect the reduction of plant and animal species and, on the other, monocultures cause significant problems in the environment and, ultimately, climate change. Conservation of biodiversity and agrobiodiversity becomes a reservoir of diversity that can be used for a successful transition under the influence of climatic changes. In this way, shortages of certain crops or difficulties in breeding certain animal species can be prevented or eliminated.

Global activities in the form of international regulations and the establishment of funds for the protection of biodiversity need to be intensified and strengthened while the awareness of their importance should be expanded among professionals and the public in general. On the other hand, GM agriculture does not have to be a unique activity focused on limiting agrobiodiversity. All the same, it can become more successful if its business and its products are regulated not only for the benefit of private capital, but also for the benefit of the public and the entire society, as well as if the entire production of GMOs is made transparent and if monopolies owned by a few companies are prevented. Interdisciplinary communication is also necessary for comprehensive and scientifically based studies of the health and safety aspects of GM agriculture. Humanity possesses the resources for scientific-technological and organizational activity in the direction of biodiversity preservation and climate changes control, but the issue of choosing global value priorities remains open. Despite the difficulties of global mitigation of climatic changes, the possibility of regional adaptation remains almost unhindered precisely due to the preservation and development of biodiversity and agrobiodiversity.

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CHEMICAL COMPOSITION AS AN INDICATOR OF THE CALORIFIC VALUE OF PLANT BIOMASS

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Abstract: The aim of this study was to predict the calorific value of plant biomass based on its chemical composition. Lignin and ash contents, as well as elemental composition (C, H, N, O), were analyzed in biomass derived from tobacco, maize, and sunflower stalks. Using the obtained parameters, empirical equations were applied to estimate the calorific (heating) value of the biomass. The use of chemical indicators enables a rapid and reliable assessment of biomass energy potential without the need for direct calorimetric measurements. The results indicate that lignin and ash contents have a significant influence on calorific value, while elemental composition allows for more precise quantification. The obtained data provides a basis for optimizing the utilization of plant biomass in biofuel production and thermal energy generation, thereby contributing to the sustainable use of renewable energy sources.

Keywords: Plant biomass, Calorific value, Lignin, Ash, Elemental composition, Prediction, Biofuel

INTRODUCTION

The utilization of renewable energy sources represents one of the most relevant challenges in developed countries worldwide. In this context, biomass stands out as a particularly important renewable energy resource, with a steadily increasing share in national energy balances, including that of Serbia. Although Serbia possesses considerable renewable energy potential, available data on the economic feasibility of its large-scale application remain limited (Jevtić and Ivkov, 2021).

It is estimated that approximately 12.5 million tons of agricultural biomass are available annually in Serbia, of which about 9 million tons originate from the Autonomous Province of Vojvodina. Given that arable land accounts for around 50% of the national territory and forests approximately 30%, the largest proportion of available biomass is derived from agricultural residues (Savić and Adžić, 2013).

The Serbian energy sector is characterized by numerous structural challenges, including low energy efficiency in both production and consumption, outdated technologies, insufficient investment, relatively low electricity prices, a limited share of renewable energy sources in total energy consumption, and pronounced inefficiencies in energy use. Consequently, the broader application of biomass remains constrained by high collection and transportation costs, fragmentation of agricultural holdings, and temporal mismatches between biomass generation and utilization (Ećim-Đurić et al., 2020).

Despite these limitations, Serbia has significant potential for biomass utilization in combined heat and power (CHP) systems. Government projections for renewable energy capacity development in the period 2015-2030 emphasize the important role of renewable sources in the country's future of energy. According to the Energy Development Strategy of the Republic of Serbia until 2025, with projections to 2030, biomass represents the largest share of renewable energy potential, accounting for approximately 61% of the total available potential. For this reason, biomass has been identified as the most important renewable energy resource available in Serbia (Martinov et al., 2015).

The use of wood pellets and briquettes is already widespread, while increasing attention is being directed toward the production and utilization of biofuels derived from agricultural crop residues (Kuthe et al., 2021). In this context, tobacco stalks constitute a significant fraction of the total available agricultural biomass in Serbia (Kulić et al., 2025). According to data from the Statistical Office of the Republic of Serbia, large-leaf tobacco varieties were cultivated on an area of 4.116 ha in 2024 (Statistical Office of the Republic of Serbia, 2025). Considering an average plant density of approximately 22.500 stalks per hectare and an average stalk mass of 400 g, the total number of tobacco stalks produced is estimated at approximately 92.6 million (Radojčić, 2011).

In 2024, maize was cultivated on an area of 987.492 ha (Statistical Office of the Republic of Serbia, 2025). The number of maize stalks varies, typically ranging from 50.000 to 65.000 plants per hectare, with an average stalk mass of 350 g (Kovačević, 2001), depending on hybrid selection, soil type, and sowing method, with the aim of achieving optimal crop density and high yield. Sunflower was cultivated on an area of 248.607 ha (Statistical Office of the Republic of Serbia, 2025), with an average stalk weight of 400 g and approximately 50.000 stalks per hectare (Kovačević, 2001).

These data clearly indicate the substantial energy potential of tobacco, maize, and sunflower stalks as alternative biofuels.

Available estimates suggest that agricultural biomass can fully meet the energy demands of the agricultural sector itself. Approximately 25% of the total biomass generated in agricultural production can be utilized for thermal energy, corresponding to about 3 million tons of biomass, which is equivalent to approximately 1.05 million tons of fuel oil (Statistical Office of the Republic of Serbia, 2021).

From an environmental protection perspective, the combustion of agricultural biomass is considered environmentally justified, as it results in lower emissions of harmful substances compared to conventional fossil fuels. Notably, biomass combustion does not lead to an

increase in CO₂ emissions, while emissions of sulfur oxides are negligible (Brkić et al., 2007).

The research presented in this paper contributes to the assessment of the energy potential of tobacco stalks, with particular emphasis on Burley-type tobacco, which is distinguished by its specific stalk-curing method. Previous studies have largely overlooked tobacco stalks as a potential biofuel, especially under domestic conditions, although they are classified as non-hazardous waste under current regulations (Waste Catalogue, 2010). These considerations provided the primary motivation for the present study.

Accordingly, the aim of this research was to estimate the heating value of Burley-type tobacco stalks as a potential biofuel based on their elemental composition, lignin content, and ash content. The obtained results were compared with the heating values of maize and sunflower stalks, which represent major crops in Serbian agriculture, with all values calculated using the same methodology.

MATERIAL AND METHODS

Experimental research was conducted on three different types of biomass: Burley-type tobacco stalks, maize stalks, and sunflower stalks. The stalks were obtained from individual agricultural producers in the Stara Pazova production area. Biomass preparation involved gradual air-drying followed by grinding to obtain a homogeneous mass. In accordance with standard methods for determining the physicochemical properties of biomass, the following parameters were analyzed: ash content determined according to SRPS EN 14775:2011, and lignin content, determined using the TAPPI method (TAPPI Test Method T 222 om-02). Elemental composition (C, H, N, and S) was determined instrumentally using an Elementar Vario EL III elemental analyzer (Elementar GmbH, Germany), in accordance with EN 15104:2011 for the determination of carbon, hydrogen, and nitrogen, and EN 15289:2011 for the determination of sulfur. Oxygen content was calculated by difference.

The prediction of higher heating value (HHV), expressed as the calorific value, was calculated using three empirical equations based on the previously determined lignin content, ash content, and elemental composition of the investigated biomass.

The calculation of HHV (calorific value) was performed using the following equations:

$$\text{HHV} = 19.914 - 0.2324 (A) \quad (\text{Sheng and Azevedo, 2005}), \text{ where } A \text{ is ash content} \quad (1)$$

$$\text{HHV} = 0.0889 (L) + 16.8218 \quad (\text{Demirbas, 2001}), \text{ where } L \text{ is lignin content} \quad (2)$$

$$\text{HHV} = -1.3675 + 0.3137 (C) + 0.7009 (H) + 0.0318 (O) \quad (\text{Sheng and Azevedo, 2005}) \quad (3)$$

where C, H, and O represent the mass fractions of carbon, hydrogen, and oxygen respectively.

Equation (3) is one of the most reliable, with an estimated uncertainty of $\pm 5\%$. Using these equations, HHV values were calculated for all investigated biomass samples, and the results are presented in Table 2. To determine the presence of statistically significant differences among HHV values calculated using different empirical equations, as well as to compare HHV values between the investigated biomass samples, a one-way analysis of variance (ANOVA) was applied.

RESULTS AND DISCUSSION

Table 1 presents the results of the chemical composition analysis (lignin content, ash content, and elemental composition) of large-leaf Burley-type tobacco stalks and two additional biomass samples included for comparison of HHV values. Based on the determined lignin and ash contents, ash content and elemental composition, HHV values were calculated using the previously described equations.

The results of the chemical analysis indicate that Burley tobacco stalks have the highest lignin content (18.36%). Mijailović et al. (2014) calculated, based on lignin content, that tobacco stalks have an HHV of 18.308 MJ/kg and a relatively low ash content (4.24%), while maize stalks contain the lowest lignin content (12.75%) and the highest ash content (6.49%). According to previous research results (Badger, 1999; Mijailović et al., 2014; Malnar et al., 2015a), the expected ash content in biomass is below 10%, which was confirmed for all investigated samples. Sunflower stalks exhibited moderate lignin content (16.43%) and the lowest ash content (4.06%). With respect to elemental composition, sunflower stalks had the highest carbon content (47.50%) and the lowest oxygen content (39.62%), indicating more favorable energy characteristics compared with the other analyzed biomass samples.

Table 1. Chemical Composition of Tobacco Stalks and Other Biomass Samples (%)

Samples	Lignin	Ash	Elemental Composition		
			C	H	O
Burley stalk	18.35694	4.24128	44.03	7.02	43.27
Maize stalk	12.75476	6.48624	44.75	5.80	41.76
Sunflower stalk	16.42938	4.05657	47.50	5.52	39.62

By calculating HHV values using the three aforementioned equations, results were obtained from five replicates for tobacco stalks and for the two biomass types most commonly produced in Serbia. The mean calorific values are presented in Table 2. The calculated average HHV values indicate that sunflower stalks achieve the highest HHV according to all three applied equations (18.28-18.97 MJ/kg), while maize stalks show the lowest HHV values (17.96-18.41 MJ/kg). Burley-type tobacco stalks exhibit comparable and consistent HHV values (18.45-18.93 MJ/kg), which are slightly lower than the value of 18.94 MJ/kg reported for Burley-type tobacco from the Čoka region (Radojičić et al., 2014a). This reported value lies between those obtained for sunflower and maize biomass. The observed deviations among the applied equations are small, indicating good agreement in estimating the energy value of the investigated samples.

Table 2. Average HHV Values (MJ/kg)

	HHV (1)	HHV (2)	HHV (3)
Burley stalk	18.928326	18.453732	18.816846
Maize stalk	18.406598	17.955698	18.04419
Sunflower stalk	18.971252	18.282372	18.588236

Table 3 presents the results of the statistical analysis examining the presence of statistically significant differences in HHV estimates for individual biomass samples calculated using

different empirical equations. The results of the one-way analysis of variance (ANOVA) indicate that, for Burley-type tobacco stalks, no statistically significant differences were observed among HHV values obtained using the different equations ($F = 1.86 < F_{0.05}$), confirming good agreement among the applied models and confirms the robustness and reliability of the applied predictive approach for this type of biomass highlighting the methodological significance of ANOVA.

In contrast, for maize stalks, highly significant differences were detected between HHV values using the different equations ($F = 57.27 > F_{0.01}$), while for sunflower stalks the differences were statistically significant at the 95% confidence level ($F = 26.91 > F_{0.05}$). These results indicate that the choice of empirical equation can significantly influence HHV estimation for certain types of biomass.

Table 3. Analysis of Deviations in HHV Values Calculated Using Different Equations for Each Individual Sample

Each individual Sample					
Sources of Variation n=5; k=4; N=20	Sum of Squares (SS)	Degrees of Freedom (v)	Variance (MS)	F- Statistic	F -Table $\alpha =0.01$ $\alpha =0.05$
Burley stalk					
HHV Values from Different Equations	0.629997	v ₁ =3	0.21	1.8574 ^{NS}	F _{0,05;3;16} = 3.24
Error	1.808972	v ₂ =16	0.11306		F _{0,01;3;16} = 5.29
Maize stalk					
HHV Values from Different Equations	1.944727	v ₁ =3	0.648242	57.27048 ^{**}	F _{0,05;3;16} = 3.24
Error	0.181103	v ₂ =16	0.011319		F _{0,01;3;16} = 5.29
Sunflower stalk					
HHV Values from Different Equations	1.524506	v ₁ =3	0.508169	26.9088 [*]	F _{0,05;3;16} = 3.24
Error	0.302158	v ₂ =16	0.018885		F _{0,01;3;16} = 5.29

NS-Difference is not significant, $p < 0.05^*$, $p < 0.01^{**}$

Table 4 presents the results of the statistical analysis examining differences in higher heating value (HHV) among biomass samples for each of the three applied HHV calculation equations. When the calculated F-value exceeds the corresponding critical value, the differences in HHV among biomass types are considered statistically significant, indicating that the observed variation is not due to random errors. Conversely, when the F-value is lower than the critical value, the differences are not statistically significant.

The results of the one-way analysis of variance (ANOVA) reveal highly significant differences in higher heating values (HHV) among the analyzed biomass samples for all three equations. For HHV (1), an F-value of 6.02 was obtained, exceeding the critical value at a significance level of $\alpha = 0.01$ ($F_{0.01} = 3.90$). Similarly, the calculated F-value for HHV (2) was 7.50, while an even more pronounced difference was observed for HHV (3), with an F-value of 21.45. In all cases, the calculated F-values exceeded the corresponding critical values at $\alpha = 0.01$. These results clearly indicate that biomass type has a highly

significant effect on HHV, regardless of the empirical equation applied, with the greatest difference observed when HHV is calculated using equation (3).

Table 4. Analysis of Deviations in HHV Between Different Biomass Samples Obtained Using Different Equations

Sources of Variation n=5; k=6; N=30	Sum of Squares (SS)	Degrees of Freedom (v)	Variance (MS)	F Statistic	F Table $\alpha=0.01$ $\alpha=0.05$
HHV (1)					
HHV of Different Biomass Samples	1.388704	v ₁ =5	0.277741	6.024802**	F _{0,05;5;24} = 2.62
Error	1.10639	v ₂ =24	0.0461		F _{0,01;5;24} = 3.9
HHV (2)					
HHV of Different Biomass Samples	1.129937	v ₁ =5	0.225987	7.5**	F _{0,05;5;24} = 2.62
Error	0.721405	v ₂ =24	0.03006		F _{0,01;5;24} = 3.9
HHV (3)					
HHV of Different Biomass Samples	2.526018	v ₁ =5	0.505204	21.44875**	F _{0,05;5;24} = 2.62
Error	0.565296	v ₂ =24	0.023554		F _{0,01;5;24} = 3.9

NS-Difference is not significant, $p<0,05^*$, $p<0,01^{**}$

Calorific value is a key parameter in evaluating the suitability of biomass as a fuel, as it determines the amount of energy that can be obtained under given conditions (Kulić et al., 2025). It can be determined both experimentally and through computational approaches. In this study, the higher heating value (HHV) was predicted using three empirical equations proposed by different authors, based on the previously determined lignin content, ash content, and elemental composition of the investigated biomass. Estimating calorific value from chemical composition is commonly used to obtain preliminary results, particularly when planning the introduction of a new type of biofuel in a rapid and cost-effective manner.

The chemical composition of biomass represents a fundamental parameter in its characterization for bioenergy production, as it directly influences the quality of the final product as well as compliance with relevant standards a regulatory requirement.

Elemental composition of biomass defines the mass fractions of carbon, hydrogen, sulfur, nitrogen, and oxygen, and serves an important indicator of biomass quality, as well as its potential for the formation of harmful gaseous emissions during utilization (Živković and Đorđević, 2001). Burley-type tobacco was selected because, compared with other tobacco types, it is harvested and cured on the stalk, which facilitates collection and transport and reduces the energy required for subsequent drying. Maize stalks were included due to their traditional use as biofuel, while sunflower stalks were selected because they are less commonly used.

The obtained calorific values (HHV) for all investigated samples are consistent with data reported in the relevant literature, which indicate that plant biomass typically exhibits HHV values in the range of 18.0 to 24.8 MJ/kg (Demirbas, 1997; Sheng and Azevedo, 2005;

Chun-Yang, 2011). Accordingly, based on their energy characteristics, all analyzed biomass samples can be considered suitable for use as biofuel.

CONCLUSION

The results demonstrate that Burley-type tobacco stalks exhibit higher HHV values (18.45-18.93 MJ/kg), comparable to those of the other analyzed biomass types, thereby confirming their potential for use as a biofuel. Statistical analysis indicated that, for Burley-type tobacco stalks, no statistically significant differences were observed among HHV values calculated using different empirical equations, whereas for maize and sunflower stalks, statistically significant or highly significant differences were detected. Furthermore, highly significant statistical differences were observed between the HHV values of Burley-type tobacco stalks and those of the other analyzed biomass samples.

Based on the obtained results, it can be concluded that existing empirical equations can be effectively applied to predict the calorific value of new types of biomass, providing a reliable basis for further experimental investigations and potential wider utilization. The calculation of calorific value using equations based on elemental composition, ash content, and lignin content confirmed that the investigated stalks possess favorable energy characteristics and can be used as biofuels. Moreover, predicting the calorific value of Burley-type tobacco stalks enables the development of future studies focused on the economic feasibility of their utilization, either as a standalone biofuel or in combination with other available agricultural residues in Serbia.

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ECONOMIC JUSTIFICATION OF DIFFERENT TILLAGE SYSTEMS IN AGRICULTURAL PRODUCTION

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Abstract: The application of different tillage systems also has an economic dimension of justification. Agroecconomics 2024/2025 an experiment with wheat on an area of 1 ha was established on the experimental field of the Research and Development Institute "Tamiš" from Pančevo, which was grown in a system of conventional and zero tillage. The aim of this research was to determine the economic benefits that can be realized depending on the applied soil cultivation system. The comparability of the results was achieved by calculating the gross coverage margin (Gcm) and the coefficient of economy of production (Cep). Both indicators (Gcm=132,898 dinars; Cep=3.5 dinars) are higher in the case of wheat cultivation in the zero-tillage system than in the case of conventional tillage.

Keywords: Economic justification, Gross coverage margin, Coefficient of economy of production

INTRODUCTION

Literature Review

In modern agricultural production, various systems of agricultural land processing are intertwined, which can directly affect the achieved economic profitability at the end of the production process. Traditional tillage dominates the world, but the interest of agricultural producers is slowly shifting to alternative tillage systems, such as conservation or zero tillage (Ahmad an Wang, 2023; Jug et al., 2025; Jayaraman and Dalal, 2022). Alternative soil cultivation systems represent a kind of response to the conservation of land resources and mitigation of climate change in the process of agricultural production (Vejedla et al., 2025; Sadiq et al., 2024; Mondal et al., 2023; Neufeldt et al., 2015).

By applying the system of reduced agricultural production, the economic and social position of producers is simultaneously strengthened (Stošić et al., 2022). The classic system of agricultural land processing creates high costs, where we primarily mean fuel and labor costs, which consequently affects financial and economic indicators and ultimately the profit of agricultural producers (Jaskulska, 2020). Therefore, the authors Wang et al. (2025) propose a transition to other tillage systems (reduced, conservation, regenerative) that achieve positive results not only in the economic sense, but also in relation to the environment, biodiversity and soil.

Switching from conventional to no-till on 1.000 acres can save about 4.160 gallons of diesel (approximately USD 8.500) per year in fuel alone, with additional savings in labor hours and machine maintenance costs (USDA, 2017).

According to the EU CAP Network (2025), reduced and no-till cultivation significantly reduces production costs in the Mediterranean parts of the EU, because it improves the soil structure, reduces erosion and increases the efficiency of inputs (labor, fuel).

In Croatia, research was conducted regarding the assessment of the economic profitability of winter wheat production with different tillage systems, and the results showed that the best economic results were achieved by wheat production without tillage (Stošić et al., 2022).

A study was conducted in Lithuania that showed that by switching from conventional to zero tillage, production costs are reduced by 23% (Saldukaitė-Sribikė et al., 2022).

In the Mediterranean and semi-arid areas of Europe, alternative agricultural land cultivation systems have a higher level of competitiveness compared to the classic land cultivation system. In Spain, no-tillage and reduced tillage have been shown to contribute to a higher value of gross margin coverage compared to traditional tillage by about 16%, especially in rotational systems of wheat and leguminous production (Serrano et al., 2011).

Overall, the literature indicates that the transition from traditional to alternative tillage systems in wheat production can bring significant economic benefits, but that their realization depends on local conditions, access to mechanization and the degree of willingness of producers to accept new technologies.

Analysis of the State of Different Agricultural Land Cultivation Systems in Europe and Serbia

In order to better observe the changes in the area cultivated and to which different tillage systems are applied per farm, we used secondary data from the internationally recognized database EUROSTAT (2025) and the electronic database of the Republic Institute for Statistics of the Republic of Serbia. For the European Union level, the analysis included the period 2016-2023. year, while the data for Serbia refer to 2012 and 2023, which are also census years. Table 1 shows changes in the size of arable land per agricultural holding, as well as the representation of different forms of land cultivation (conventional, conservation and no-till) for the EU, European countries and Serbia.

As we can see, most countries are recording an increase in arable land per farm, which indicates the continuation of the concentration (consolidation) of arable land. At the same time, there is a gradual transition from conventional to conservation tillage and the application of zero tillage methods. Serbia, although among the countries with the smallest farms, shows growth in all forms of processing, which confirms the trend of adopting more sustainable agrotechnical practices. We can conclude that there is a slow acceptance of conservation and zero tillage despite their potential to improve the sustainability of agricultural production.

Table 1. Comparative presentation of arable land and types of land cultivation by agricultural holding in EU countries (2016-2023) and Serbia (2012-2023) (ha)

Territory	Arable land per holding		Conventional tillage per holding		Conservation tillage per holding		Zero tillage per holding	
	2016	2023	2016	2023	2016	2023	2016	2023
European Union (27 countries)	20.2	-	15.5	-	32.9	-	7.8	-
Belgium	26.5	-	24.7	-	16.3	-	8.4	-
Bulgaria	49.0	77.9	34.1	49.9	53.1	67.2	53.9	207.7
Czechia	146.8	122.0	105.3	88.7	224.6	169.2	46.4	60.0
Denmark	73.2	-	67.4	-	81.0	-	40.9	-
Germany	56.1	65.2	34.5	32.3	62.0	62.4	18.7	28.4
Estonia	83.0	99.0	46.4	45.4	106.7	135.6	108.6	66.3
Ireland	23.3	-	31.2	-	30.9	-	26.0	-
Greece	6.8	7.5	7.2	7.8	3.1	4.4	1.9	2.9
Spain	28.3	33.0	26.9	27.1	20.5	23.9	24.0	33.0
France	59.0	63.3	37.4	40.5	45.9	55.6	34.3	28.0
Croatia	10.0	11.3	9.4	9.6	16.0	25.9	3.3	7.7
Italy	11.1	-	10.8	-	14.2	-	4.4	-
Cyprus	6.9	11.0	7.3	12.3	5.1	2.7	45.6	-
Latvia	31.4	-	22.9	-	106.7	-	47.5	-
Lithuania	21.1	28.1	18.4	13.4	49.4	51.9	16.3	49.1
Luxembourg	45.9	46.4	26.1	23.8	26.0	30.5	7.6	16.1
Hungary	29.2	35.2	26.9	26.3	89.4	39.3	9.6	4.3
Malta	2.1	2.1	2.1	2.0	-	-	-	-
Netherlands	24.6	27.5	20.0	20.3	16.1	18.9	5.0	7.5
Austria	20.6	23.0	13.3	13.7	22.1	25.4	8.6	6.9
Poland	11.1	13.0	10.5	10.3	29.5	11.0	33.7	28.1
Portugal	7.4	7.0	3.6	3.7	15.9	12.6	19.5	17.5
Romania	7.0	10.0	5.8	8.8	8.0	19.2	2.2	4.5
Slovenia	2.1	-	1.7	-	2.9	-	-	-
Slovakia	92.0	111.1	72.5	73.4	184.0	192.4	149.5	108.8
Finland	45.1	-	21.4	-	23.2	-	23.6	-
Sweden	42.4	46.9	32.6	44.2	37.2	18.8	19.5	8.5
Norway	20.9	-	14.9	-	11.3	-	14.6	-
Switzerland	13.5	-	6.9	-	6.2	-	3.1	-
United Kingdom	70.1	-	57.3	-	92.7	-	50.9	-
Serbia*	4.1	5.3	4.1	5.3	4.6	8.6	1.6	2.1

Source: Author's calculation based on EUROSTAT (2025) and SORS data (2025), electronic database, Census of Agriculture for 2012 and 2023; **Note:** the symbol “-” means that some data are not available for calculation, so there is no calculated value; *The data for Serbia refer to the years 2012 and 2023 because they are available for those years, and given that they are also census years.

MATERIALS AND METHODS

The paper presents the results of research according to the representation of soil cultivation systems in the European Union and European countries during 2016 and 2023, as well as in Serbia during 2012 and 2023.

The original part of the research consists of an economic evaluation of wheat production in the system of conventional and zero tillage. The data were obtained upon request from the „Tamiš“ Research and Development Institute Pančevo, Serbia, and for the purposes of making analytical calculations in wheat production with both production systems.

Realized income, agrotechnical operations and costs relate exclusively to wheat production in the system of conventional and zero tillage and may not be the same for other crops and production. The analysis was performed at the level of one production cycle (agro-economic year 2024/2025), on an area of 1 ha of arable land and is expressed in RSD.

In the preparation of the analytical calculation, certain costs were not taken into consideration, namely: the cost of purchasing the necessary machinery for the implementation of certain agrotechnical operations because the service engagement of this equipment was paid for; depreciation of existing equipment because due to their average age we believe that it does not affect the gross coverage margin; labor cost due to the fact that seasonal labor was not hired.

The data analysis is based on the Institute's internal information, primarily when it comes to the purchase prices of seeds, pesticides, fertilizers, the costs of maintaining machines and transporting wheat to warehouses. Data on the price of fuel (euro diesel) and paid mechanization services were taken from the Price List of Machinery Services in Agriculture 2024, published by the Cooperative Union of Vojvodina. These prices per unit of measure are shown without value added tax (VAT). Data on the purchase price of wheat in 2025 was taken from the website of the Novi Sad Commodity Exchange in the period 07.07 - 07.11.2025. year. Wheat yield represents the actual state of the finished agro-economic year.

The applied methodology should also be taken into account when making the analytical calculation. Total income is the product of the realized yield and the purchase price at a given time. The total variable costs were calculated based on the actual activities in the wheat production process in the system of conventional and zero tillage, namely:

- cost of wheat seeds;
- the type of fertilizers used is the same in wheat production for both tillage systems, but it was applied in different quantities. More precisely, NPK 10:46:0 was applied in the amount of 200 kg/ha and AN in the amount of 250 kg/ha in conventional wheat processing. The use of these fertilizers in the production of wheat in the zero tillage system was reduced by 50%;
- the type of pesticides used is the same in both wheat production systems, namely: Metmark, Lodin, Olimp, tetar plus, Unify, Grom and Polux;
- fuel costs are lower in wheat production in the system of zero tillage due to a significantly lower number of agrotechnical operations;
- the costs of agrotechnical operations are lower in wheat production in the system of zero tillage due to the reduced number of machine operations (sowing and harvesting costs).
- other variable costs (costs of maintaining machines and transporting wheat to the warehouse) occurred in both wheat production systems and are of the same value;

- the costs of cover crops in the production of wheat in the system of zero tillage are not shown, considering that vegetation is provided on the arable surface throughout the year.

After analyzing the analytical calculation, we moved on to the analysis of the critical values of wheat production in the system of conventional and zero tillage according to the following equations (equations 1, 2 and 3):

$$CP = \frac{VC-S}{EY} (1), CY = \frac{VC-S}{EP} (2), CVC = (EY * EP) + S (3)$$

where is: CP - critical price, VC - variable costs, S - subsidies, EY - expected yield, CY - critical yield, EP - expected price, CVC - critical variable costs.

The analysis of the analytical calculation of wheat production in both production systems continued with the assessment of the sensitivity of the gross margin in wheat production depending on the change in yield (t/ha) and purchase price (RSD/t), and in accordance with the obtained results, an adequate comment was given.

Finally, the efficiency coefficient of wheat production in the system of conventional and zero tillage was calculated according to the following equation (4):

$$\text{Coefficient of economic of production (Cep)} = \frac{\text{Production value}}{\text{Total costs}} \quad (4)$$

All tables and comments retain the presentation of data in the national currency (RSD). This part shows the average exchange rate of the Serbian dinar against the euro (1 EUR = 117.1666 RSD) on the reference date (July 11, 2025) in order to enable comparison and interpretation of values ().

The research used the method of descriptive statistics, analysis of quantitative indicators, as well as induction and deduction in drawing conclusions.

RESULTS AND DISCUSSION

In this part of the paper, indicators of the economic sustainability of conventional and zero tillage in wheat production will be presented based on the experiment set up on the experimental field of the „Tamiš“ Research and Development Institute Pančevo, Serbia. Given that agricultural production consists of many factors, it is necessary to take into account the value and costs of production for the assessment of economic results (Subić et al., 2023).

Economic Assessment of Wheat Production in the System of Conventional Tillage

According to the previously defined methodology, we moved on to the analysis of the economic assessment of wheat production in the system of conventional tillage. Accordingly, Table 2 shows the calculation of the gross margin of wheat production per 1 ha.

Table 2. Calculation of the gross margin of wheat production per 1 ha of arable land in the system of conventional tillage

Category	Value (RSD/ha)
I Total income	148,000
II Variable costs	91,326
Seeds	9,900
Fertilizer	26,288
Pesticides	6,598
Diesel fuel	6,060
Paid services by machinery	37,160
Other variable costs	5,320
III Gross margin	56,674

Source: author's calculation based on the Institute's internal data

The total estimated variable costs of RSD 91,326/ha actually make up more than half of the total income (61.7%), which is why it is considered insufficient and economically justified. Certainly, the highest cost value is the expenditure for paid services by mechanization, then for fertilizer, and together they make up close to 70% of the total variable costs in the production of wheat in the system of conventional tillage.

The value of the gross margin of RSD 56,674/ha shows us the low level of profitability of wheat production, and this result may indicate the necessary optimization of certain inputs in those segments where there are opportunities for greater savings or efficiency.

In the continuation of the analysis, a tabular overview of the critical values of wheat production in the conventional production system was given, and the parameter values were calculated based on the equation presented in the methodological part of the paper.

Table 3. Critical values of yield and price of wheat in the system of conventional tillage on an area of 1 ha

Category	EY, t/ha	EP, RSD/t	S, RSD	VC, RSD/ha	CP, RSD/t	CY, t/ha	CVC, RSD/ha
Value	6.5	20,000.0	18,000.0	91,326.0	11,280.0	3.7	148,000.0

Source: author's calculation based on the Institute's internal data

In order to achieve a neutral coverage margin, the purchase price of wheat must not be less than RSD 11,280.9/t, the yield minimum 3.7 t/ha, and the total variable costs must not exceed the total income (RSD 148,000/ha).

The next table (Table 4) shows the sensitivity analysis of the gross margin in wheat production in the system of conventional tillage depending on the change in yield (t/ha) and purchase price (RSD/t). Deviations from expected values for both parameters of $\pm 10\%$ and $\pm 20\%$ were applied.

Table 4. Sensitivity analysis of the gross margin in wheat production in the system of conventional tillage on an area of 1 ha

Price change		Price (RSD/t)				
Yield change		-20%	-10%	Realized	+10%	+20%
Yield (t/ha)		16,000.0	18,000.0	20,000.0	22,000.0	24,000.0
-20%	5.2	9,874	20,274	30,674	41,074	51,474
-10%	5.9	20,274	31,974	43,674	55,374	67,074
Realized	6.5	30,674	43,674	56,674	69,674	82,674
+10%	7.2	41,074	55,374	69,674	83,974	98,274
+20%	7.8	51,474	67,074	82,674	98,274	113,874

Source: author's calculation based on the Institute's internal data

The results clearly indicate that the total income from production depends on the value of yield and prices. In this example, we see that in the case of a 20% increase in yield and price, the income per hectare is RSD 113,874, which is more than double compared to the situation where both parameters are lower by 20% (RSD 9,874/ha).

In general, any positive change in one of the variables leads to a proportional increase in income, while negative changes, especially if they occur simultaneously, significantly reduce the financial result. Such results emphasize the importance of risk management strategies in agricultural production, both in terms of yield stabilization (eg through agrotechnical measures) and in terms of protection against market fluctuations (eg through contractual sales or insurance).

Based on the obtained values in the calculation of the gross margin of wheat production in the conventional production system, we can also determine the efficiency coefficient of wheat production, and the equation for the calculation is presented in the methodological part of the paper. In our case, the coefficient of economy of production is 1.6 and shows that for every RSD of expenses, 1.6 RSD of income was realized.

Economic Assessment of Wheat Production in the Zero-Tillage System

According to the previously defined methodology, we moved on to the analysis of the economic evaluation of wheat production in the system of zero tillage, and Table 5 shows the calculation of the gross margin of wheat production on an area of 1 ha.

Table 5. Calculation of the gross margin of wheat production on the surface of 1 ha of arable land

Category	Value (RSD/ha)
I Total income	187,000
II Variable costs	54,102
Seeds	9,900
Fertilizer	13,144
Pesticides	6,598
Diesel fuel	3,030
Paid services by machinery	16,110
Other variable costs	5,320
III Gross margin	132,898

Source: author's calculation based on the Institute's internal data

Total variable costs estimated at RSD 54,102/ha make up about 29% of the realized income. The largest share in the structure of variable costs is provided by machinery (29.8%) and fertilizer (24.3%). These two costs together make up 54.1% of the total variable costs in wheat production.

Table 6 shows the critical values of wheat production in the no-tillage system based on the previously set formula.

Table 6. Critical values of yield and price of wheat in the production system without tillage on the surface of 1 ha of arable land

Category	EY, t/ha	EP, RSD/t	S, RSD	VC, RSD/ha	CP, RSD/t	CY, t/ha	CVC, RSD/ha
Value	8.5	20,000.0	18,000.0	54,102.0	4,272.4	1.8	187,000.0

Source: author's calculation based on the Institute's internal data

In order to achieve a neutral coverage margin, the purchase price of wheat must not be less than 4,272.4 RSD/t, the yield at least 1.8 t/ha, and the total variable costs must not exceed the value of the total income (187,000 RSD/ha).

Table 7 shows the sensitivity analysis of the gross margin in wheat production in the no-tillage system depending on the change in yield (t/ha) and purchase price (RSD/t).

Table 7. Sensitivity analysis of the results of gross margin calculation in wheat production in a system without wheat cultivation on an area of 1 ha

Price change		Price (RSD/t)				
Yield change		-20%	-10%	Realized	+10%	+20%
Yield (t/ha)		16,000.0	18,000.0	20,000.0	22,000.0	24,000.0
-20%	6.8	72,058	85,578	99,098	112,618	126,138
-10%	7.6	85,578	100,788	115,998	131,208	146,418
Realized	8.5	99,098	115,998	132,898	149,798	166,698
+10%	9.3	112,618	131,208	149,798	168,388	186,978
+20%	10.1	126,138	146,418	166,698	186,978	207,258

Source: author's calculation based on the Institute's internal data

Even in the most unfavorable scenario (price and yield drop by 20%), the gross margin remains positive (RSD 72,058/ha), which shows the resistance of wheat production in the zero tillage system to market changes. Any increase in yield and/or price significantly increases the coverage margin, where it can be up to 1.6 times higher in the case of a 20% increase in yield and price compared to the achieved gross coverage margin.

In the end, we determined the efficiency coefficient of wheat production, which in the system without tillage is 3.5. The economy of production showed us that for every RSD of costs, 3.5 RSD of income was realized. This model provides a more sustainable basis for planning wheat production, especially in the face of an uncertain market and rising input costs.

Overall, no-till wheat production provides a different and more rational approach to inputs than conventional no-till wheat production. Also, there are obvious savings in the costs of

mechanization, fertilizers and fuel, which contributes to the economic sustainability of production.

CONCLUSION

A review of relevant domestic and foreign research confirms that, although conventional tillage is still dominantly applied in many countries, a gradual but continuous shift towards alternative land tillage systems, primarily reduced and zero tillage, is observed, especially in conditions of rising input costs.

Overall, the research results confirm that zero tillage represents a more economically viable and stable wheat production system compared to conventional tillage, especially in the face of rising input costs and market uncertainty. In addition to its cost-reducing effects, zero tillage contributes to greater production efficiency and improves the resilience of farming systems, which is particularly important in conditions of increasing price volatility of agricultural inputs and growing climate-related risks.

However, the scope of this research also opens several directions for future studies. Further research could expand the analysis to include a longer time horizon and a larger sample of farms, as well as other crop types, in order to assess the long-term economic and environmental effects of different tillage systems. Moreover, integrating indicators of soil quality, carbon sequestration, and yield stability would enable a more comprehensive evaluation of the sustainability of zero tillage systems. Future studies could also apply advanced econometric methods or panel data analysis to better capture regional heterogeneity and the dynamic effects of technology adoption in agricultural production.

From a policy perspective, the findings of this study provide important implications for decision-makers in the agricultural sector. The demonstrated economic advantages of zero tillage suggest that public policies should further encourage the adoption of conservation tillage practices through targeted subsidies, investment support for appropriate machinery, and advisory services aimed at knowledge transfer. In countries such as Serbia, where farm size remains relatively small, tailored policy measures could play a crucial role in reducing financial barriers to adoption and supporting farmers during the transition period. Additionally, incorporating zero tillage into agri-environmental and rural development programs could contribute not only to improved farm profitability but also to broader environmental and sustainability objectives.

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PROJECT MANAGEMENT IN THE BIOECONOMY AND CIRCULAR ECONOMY

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Abstract: Integrating project management into bioeconomy and circular economy improves efficiency, sustainability, and resource optimization. Structured planning enables projects to meet goals on time and within budget while reducing waste and environmental impact. Effective coordination supports interdisciplinary collaboration and clear goal achievement. Regulatory differences across regions remain a key challenge. The paper analyses benefits, limitations, and recommendations, illustrated with a practical example.

Keywords: Project management, Bioeconomy, Circular economy, Efficiency, Environment

INTRODUCTION

Bioeconomy is an innovative approach that uses renewable biological resources such as biomass, bio-waste, plants, and microorganisms to create economic and ecological values. According to the Global Bioeconomy Summit (2018), bioeconomy includes “the production, use, and conservation of biological resources, including related knowledge, science, technology, and innovation, to provide products, processes, and services across all economic sectors aimed at a sustainable economy” (Boliko, 2019). Similarly, the National Academies of Sciences emphasize that bioeconomy “enables the conversion of renewable biological resources into food, bio-based products, and energy, reducing dependence on fossil resources and supporting sustainable development” according to National Academies of Sciences, Engineering, and Medicine. (NASEM, 2020).

This approach also supports the circular economy, where resources are maximally used, recycled, and returned to production cycles, minimizing waste and protecting the environment (Popović et al., 2022). In this context, project management plays a key role, as it allows for systematic planning, organizing, and implementing projects in an efficient and effective way. Well-managed projects not only increase productivity and economic viability but also contribute to sustainable use of biological resources, reduce waste, and optimize processes. The aim of this study is to show how the application of project management principles can significantly improve the efficient and sustainable use of biological resources and support the development of innovative and environmentally friendly solutions within the bioeconomy.

The bioeconomy focuses on the sustainable valorization of biological resources, whereas the circular economy provides the operational framework for closing material and resource loops. Integrating both approaches enables the development of a circular bioeconomy that supports green growth, innovation and environmental protection (Figure 1).

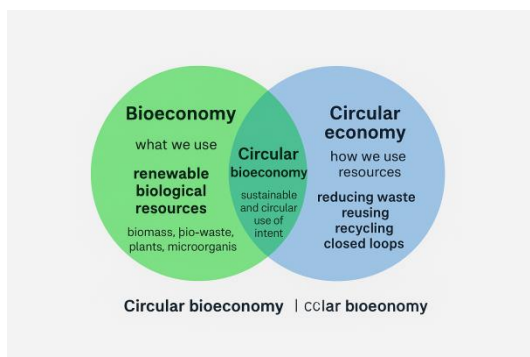


Figure 1. Bioeconomy and Circular economy
Source: Authors illustration

Bioeconomy is a broad concept based on the sustainable use of renewable biological resources, while circular economy represents a resource-efficiency model applicable across all sectors. Their intersection forms the circular bioeconomy, which promotes closed-loop use of biological resources with minimal environmental impact.

Literature Review

Concept of Bioeconomy

Bioeconomy is seen as an analytical concept, a dynamic sector of the modern economy using biological resources for food, medicine, industrial products, and energy, and a strategic tool for planning, research, and sustainable development. The study highlights the importance of technological advances, rational resource management, and integration with sustainable development to promote economic, regional, and sectoral growth (Adamowicz, 2017).

Bioeconomy inherently supports a circular economy by using renewable biomass in cyclical processes that minimize waste, recycle carbon, and aim to reduce the need for new resource inputs, thereby promoting sustainability and mitigating climate change. (Yadav et al., 2021).

Transitioning to a sustainable biocircular economy using renewable, bio-based materials while minimizing waste and following strategic principles can simultaneously address climate change, biodiversity loss, and social equity, but requires careful management to avoid “biowashing”. Considering the extreme effects of the climate crisis and the urgent need to achieve sustainable development goals, managers, companies, and entire industries must transition to a sustainable, biocircular economy, enabling all stakeholders and our planet to thrive in the future (Marshall et al., 2023).

Both the bioeconomy and circular economy, although promoted as tools for sustainability, currently pay insufficient attention to biodiversity and social equity (Stephenson and Damerell, 2022). The concepts are not clearly defined, their implementation is inconsistent, and monitoring of impacts is underdeveloped. To truly achieve sustainability, it is necessary to harmonize definitions, involve civil society, establish effective governance frameworks, foster innovation, and monitor impacts on nature and people. The focus should be on preserving species, ecosystems, and the well-being of local communities (Stephenson and Damerell, 2022).

Project Management in Sustainable Projects

Project management in sustainable projects involves organizing and guiding a project through its key phases planning, implementation, monitoring, and evaluation while integrating sustainability principles at every step. Sustainable project management expands traditional project approaches by considering environmental, social, and economic impacts throughout the project life cycle (Deland, 2009). The first phase, planning, is crucial because it defines project goals, identifies stakeholders, allocates resources, and incorporates sustainability criteria early on to reduce risks and negative impacts on people and the environment. As one study notes, “sustainable project planning assists in guiding the project team in execution, controlling and monitoring the project and can lead to identifying and minimizing project risks” (Chow et al., 2021).

During the implementation phase, the project plan is put into action, and sustainability practices such as resource efficiency, waste reduction, and stakeholder engagement are actively applied. Effective implementation ensures that sustainability targets are met alongside traditional performance metrics like time and cost. The monitoring phase involves continuously tracking progress and sustainability indicators, such as environmental performance or social outcomes, to ensure the project remains aligned with its sustainability goals. Finally, the evaluation phase assesses the overall project results, including sustainability impacts, lessons learned, and opportunities for future improvement. By systematically integrating these phases, sustainable project management not only seeks successful project delivery, but also minimizes resource use and supports long-term sustainability outcomes (Deland, 2009).

Link Between Bioeconomy and Project Management: Insights from Studies and Best Practice Examples

The connection between bioeconomy and project management lies in the need to plan, organize, implement, monitor, and evaluate complex initiatives that advance sustainable and circular use of biological resources. Research on sustainable bioeconomy strategies highlights the importance of structured planning and stakeholder coordination to achieve environmental, social, and economic goals. For example, studies on smart and sustainable bioeconomy platforms emphasize that effective bioeconomy development involves planning and stakeholder management as a core phase of strategy implementation, which aligns with project management processes such as defining goals, coordinating stakeholders, and setting performance indicators (D’Amico et al., 2022).

Moreover, research exploring sustainable development frameworks in bioeconomy shows that monitoring and evaluation practices, which are key components of project management, can support tracking progress toward sustainability objectives and help integrate bioeconomy actions with global goals such as the Sustainable Development Goals (SDGs) (Calicioglu and Bogdanski, 2021). These frameworks suggest that applying systematic project management principles including goal setting risk assessment, and performance tracking enables bioeconomy initiatives to be more transparent and effective in achieving sustainable outcomes.

Practical examples also illustrate how project management is integral to implementing large bioeconomy initiatives. European Union bioeconomy programs such as those funded through Horizon 2020 and Horizon Europe rely on structured project cycles and management frameworks to deliver complex research and innovation results, including integrated biorefineries and biomass valorization projects, demonstrating how strategic project planning and governance drive tangible bioeconomic impacts (European Commission, 2020).

Overall, studies and practice examples indicate that project management provides the tools and frameworks needed for the successful implementation of bioeconomy strategies, helping to align technical innovation with sustainability principles, manage multi-stakeholder collaborations, and monitor progress toward long-term ecological and economic objectives.

Methodology

The methodology of this study combines several qualitative research approaches to examine the link between bioeconomy and project management. First, an analysis of expert literature and reports was conducted, reviewing scientific papers, policy documents, and industry publications to gather existing knowledge, identify trends, and understand both theoretical and practical frameworks in the bioeconomy sector. Next, successful projects were identified and analyzed through case studies to explore best practices and provide concrete examples of how project management principles are applied in real-world sustainable initiatives. Finally, a qualitative assessment was carried out to evaluate the effectiveness of project management in promoting sustainable resource utilization, focusing on how planning, implementation, monitoring, and evaluation phases contribute to environmental, economic, and social outcomes. By integrating these methods, the study offers a comprehensive understanding of the role of project management in supporting sustainable bioeconomy practices and highlights strategies that can enhance both efficiency and sustainability. The selection of the case study was based on its relevance, level of development, and capacity to practically demonstrate the principles of the circular bioeconomy under real industrial conditions. Eco-Recycling d.o.o. was chosen as a representative example of best practice due to its long-term operation and the application of a closed-loop recycling model that integrates waste management, material recovery, and value creation.

Case study - Best Practice Example of ECO-RECYCLING Tire Facility

Eco-Recycling d.o.o. from Novi Sad stands out as a comprehensive and well-established example of circular economy best practice in Serbia, operating as the country's first

dedicated tire recycling facility since 2009 and fully licensed for storage, treatment, disposal, and transport of non-hazardous waste in compliance with domestic regulations and EU environmental standards (ISO 9001:2015 and ISO 14001:2015). The recycling complex in Sirig covers approximately 54.500 m² and includes large storage and handling areas as well as state-of-the-art production halls equipped with advanced machinery capable of processing all types and sizes of tires, including large damper tires, with an annual capacity of around 36.000 tons of rubber waste, producing granulates of up to 99% purity without generating additional waste or harmful emissions. Eco-Recycling not only collects and purchases waste tires from both individuals and legal entities offering transport services when needed but also integrates the entire recycling process into new value chains: recycled rubber granulate is used in a wide range of applications such as road construction materials, sports and recreational surfaces, building and agricultural products, and household items, thereby significantly reducing reliance on virgin resources and mitigating the environmental impact of non-biodegradable waste. By investing in skilled personnel and cutting-edge technology, maintaining strong operational standards, and creating secondary materials with diverse industrial uses from traffic infrastructure and sports facilities to insulation and rubber components for everyday use Eco-Recycling effectively demonstrates how sustainable industrial practices can be scaled locally while contributing to Serbia's broader circular economy goals and environmental protection efforts (Eco Recycling, 2025).

Project

The project focuses on the management of rubber waste, specifically end-of-life car and truck tires, through recycling and conversion into high-quality rubber granulate. This aligns with circular bioeconomy principles by transforming waste into reusable materials.

Project Objectives

Waste reduction, circular use of resources, and economic sustainability. Reduce tire waste and prevent environmental pollution. Promote circular use of rubber resources. Ensure economic sustainability by producing valuable products for multiple industries (construction, sports surfaces, agricultural applications).

Project Approach

Resource planning, team organization, progress monitoring, and evaluation of results.

Results

Recycled materials, energy efficiency, economic contribution.

Lessons Learned and Recommendations

Key insights for improving future projects. Importance of investing in employee training to maintain operational efficiency and quality. Demonstrates how circular economy principles can be applied to industrial waste management. Encourages replication of similar projects in other waste sectors to promote sustainability.

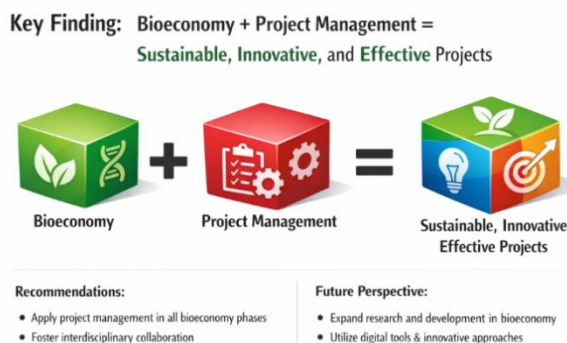


Figure 2. Sustainable, innovative and effective projects
Source: Authors illustration

DISCUSSION

Integrating project management into bioeconomy initiatives offers clear advantages that can enhance the effectiveness and sustainability of these projects. One of the primary benefits is resource optimization, as project management ensures that human, financial, and material resources are allocated efficiently, reducing waste and maximizing outputs in systems that rely on renewable biological materials. Additionally, better coordination among interdisciplinary teams including scientists, engineers, policymakers, and industry stakeholders facilitates smoother collaboration, reduces redundancies, and ensures that objectives are clearly communicated and achieved. These factors collectively contribute to higher efficiency, allowing bioeconomy projects to meet their targets on time and within budget, while also minimizing environmental impacts and promoting sustainable outcomes.

However, the implementation of project management in bioeconomy contexts is not without challenges. Regulatory issues pose significant obstacles, as projects often operate across different regions with varying environmental, safety, and industrial standards, making compliance complex. Financing is another key challenge, since bioeconomy initiatives frequently require substantial initial investment in infrastructure, technology, and skilled personnel, and funding sources can be uncertain or fragmented. Finally, technological limitations can hinder progress, as advanced equipment and processes such as biomass processing, bioproduct development, and circular resource utilization are often necessary but costly or not widely available.

To overcome these challenges, several strategies can be applied. Innovation is essential, enabling the development of new biotechnologies and the optimization of existing processes to improve efficiency and reduce costs. Education and capacity building help equip stakeholders with the knowledge and skills needed to navigate complex regulatory environments, adopt best practices, and implement sustainable solutions effectively. Furthermore, digital resource management tools and project management software can enhance monitoring, facilitate real-time decision-making, and improve overall coordination among teams. By combining these strategies, bioeconomy projects can not

only address their operational and regulatory challenges but also maximize their social, economic, and environmental impact, ensuring long-term sustainability and success.

CONCLUSION

Project management involves organizing and leading a project through the key phases: planning, implementation, monitoring and evaluation. In order for projects to be sustainable, sustainability principles need to be integrated into that every step. Sustainable project management extends traditional project approaches by taking into account environmental, social and economic impacts throughout the project life cycle.

Project management in the bioeconomy and circular economy involves the use of planning, organizing, implementing, monitoring and evaluating complex initiatives that promote the sustainable and circular use of biological resources. Structured planning and coordination of stakeholders are particularly important in order to achieve environmental, social and economic goals. In this way, sustainable project management strives for successful project implementation, minimizes resource use and supports long-term sustainability outcomes.

EU programs funded through Horizon 2020 and Horizon Europe, for example, rely on structured project cycles and governance frameworks to deliver complex research and innovation outcomes, including integrated biorefineries and biomass valorization projects, demonstrating that strategic planning and project management drive tangible bioeconomy impacts. Practice shows that project management provides the tools and frameworks needed for the successful implementation of bioeconomy strategies, helps align technical innovation with sustainability principles, and manages multi-stakeholder collaboration and monitors progress towards long-term environmental and economic goals.

A key finding of our research is that the implementation of project management into bioeconomy and circular economy lead to sustainable, innovative and efficient projects. Based on all of the above, it can be recommended that project management be included in all phases of bioeconomy and circular economy initiatives. In future research, we can pay more attention to the opportunities for research and development in the bioeconomy and circular economy sector.

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KNOWLEDGE TRANSFER ON ORGANIC PRODUCTION FOR SUSTAINABLE AND ECOLOGICAL AGRICULTURE IN SERBIA

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Abstract: The transfer of scientific knowledge in the field of organic production is a prerequisite for the development of sustainable and environmentally friendly agriculture, particularly in countries where this type of production is still emerging. This study aims to provide a comprehensive overview of the results of agricultural advisor training in organic production from 2019, as well as the methods used to transfer acquired knowledge from advisors to agricultural producers during the period 2020-2024. The analysis of advisor training data included both quantitative and qualitative indicators, enabling assessment of the scope and dynamics, content and quality of the training, as well as knowledge improvement and evaluation of applicability. The analysis of subsequent knowledge transfer from advisors to producers included quantitative indicators, such as the number of advisory educational activities conducted and the number of participating producers. The results of the advisor training show a high level of participant satisfaction (average score 4.65 out of 5), significant improvement in participants' knowledge (38.38%), and a high level of practical applicability of the training (average score 4.87 out of 5), confirming the relevance of the content and the adequacy of the educational methods used. The results of knowledge transfer from advisors to producers indicate a systematic and diverse approach to training - lectures, workshops, panel discussions, winter schools, and demonstration farms - as well as active producer participation, evidenced by a total of 19,895 participants. Based on the results of the study, it can be concluded that agricultural advisor training has strengthened the capacities of the advisory service and, in a broader context, has enhanced the efficiency of scientific knowledge transfer to producers, representing an important foundation for the long-term development of organic, sustainable, and environmentally friendly agriculture in Serbia.

Keywords: Education, Advisors, Producers, Transfer of scientific knowledge, Organic production

INTRODUCTION

Contemporary challenges in agricultural production highlight the need for transformations aimed at improving sustainable practices, while simultaneously considering the environmental, economic, and social dimensions of sustainability (Boroš et al., 2024). The link between modern agriculture and the sustainability of agricultural systems, based on the smart use of renewable resources and the regeneration of resources, is also emphasized by Kovačević et al. (2020). These authors point to the existence of various agricultural pathways, ranging from conventional production, through integrated systems, to approaches grounded in strictly ecological principles of cultivation, such as organic and biodynamic farming. Long-term experimental research comparing organic and

conventional cropping systems shows that organic approaches reduce the use of pesticides and mineral fertilizers, improve soil health, biodiversity, and nitrogen-use efficiency, while yields can reach up to 85% of those achieved under conventional systems (Krause et al., 2024). Organic production is increasingly recognized as an important instrument for sustainable rural development and ecosystem protection (IFOAM, 2022), and according to Clark (2020), organic farming has experienced remarkable growth in recent decades, driven by increased societal interest in environmental protection and healthy diets.

Globally, the area under organic agriculture has shown continuous growth; however, its share of total agricultural land remains relatively low. Organic agriculture is practiced worldwide in 188 countries on more than 96 million hectares, involving over 4.5 million farmers. These figures clearly demonstrate the growing importance of organic production in the global market (Willer, 2024). Within the framework of the “Farm to Fork” strategy, the European Union has set an ambitious target of at least 25% of agricultural land under organic management by 2030 (European Commission, 2020). In this context, candidate countries, including the Republic of Serbia, face additional challenges related to the adaptation of production systems, institutional support, and the development of knowledge and competencies among all actors in the organic production value chain.

In Serbia, organic agriculture is undergoing gradual development and has shown growth over the past decade (Simić et al., 2025). This sector is regulated by the Law on Organic Production and has been recognized as an important area in both the previous Strategy of Agriculture and Rural Development of the Republic of Serbia (2014-2024) and the Draft Strategy of Agriculture and Rural Development (2025-2034). In 2022, organic crop production in Serbia was established on 25,035 ha, of which 16,712 ha were arable land and 8,323 ha were meadows and pastures (RSZ, 2023).

Successful organic production requires efficient knowledge transfer and application. Key challenges include adapting expert knowledge to local conditions, strengthening the role of advisory services, and better integrating sustainability and agroecological principles (Milardo, 2025). Agricultural advisors play a crucial role in this process, serving as the direct link between research institutions and agricultural producers (Tolimir et al., 2025a). Their ongoing education across various fields of modern agriculture, including organic production, is essential for the effective implementation of contemporary agroecological practices, proper management of conversion processes, compliance with certification requirements, and overall improvement of production sustainability (Rivera and Qamar, 2003; Röling, 2009).

In Serbia, with the aim of strengthening the competencies of agricultural advisors, a continuous education system has been established, defined by the Regulation on the Medium-Term Programme for the Development of Agricultural Advisory Services for the period 2021-2025, and, at the annual level, by the Regulation on the Annual Programme for the Development of Agricultural Advisory Services, for example for 2024 (Regulation, 2024). Within the advisory system, the knowledge transfer process begins with transferring knowledge from knowledge creators (faculties, research institutes, ministries) to advisors through training activities based on the “train-the-trainer” principle. The next step is transferring the acquired knowledge from advisors to producers, as end users, through individual and group advisory methods.

Many authors have emphasised that continuous professional development and capacity building of advisors are prerequisites for their effective performance and ability to respond to the complex demands of modern agricultural production and current trends in agriculture (Leeuwis and van den Ban, 2004; Stanković et al., 2015; Tolimir et al., 2025b; Simić et al., 2025b). In European Union countries, the importance of education is recognised and defined by EU Regulation No. 1305/2013, which states that, to increase the quality and effectiveness of advisory services, a minimum level of professional competence and regular training of advisors must be ensured. Experiences from Poland indicate that advisory services play a significant role in this process; however, their capacities are often limited by a lack of specialised staff and adequate institutional support (Śpiewak and Jasiński, 2019). A good example of improving practical knowledge transfer is the BioRegio Betriebsnetz (BRB) network in Bavaria, which brings together experienced organic farmers and enables them, with institutional support and minimal administrative burden, to serve as examples of good practice and complement the work of existing advisory services (Hinzpeter, 2025).

The aim of this paper is to present the effects of agricultural advisor training conducted from 2019 to 2024, as well as the scope and forms of subsequent knowledge transfer to producers through advisory and educational activities, and to highlight the importance of advisory work in supporting the development of organic production and sustainable agriculture in the Republic of Serbia.

MATERIAL AND METHODS

The study focuses on the analysis of data related to the training of advisors of the Agricultural Extension and Expert Services of the Republic of Serbia (PSSS), responsible for activities in the fields of crop production, livestock production, fruit growing, and plant protection, during the period from 2019 to 2024. Within this period, training programmes for advisors in organic agriculture, implemented according to the “train-the-trainers” principle, were conducted in 2019, 2021, and 2022. Based on the knowledge acquired through advisor training, training programmes for producers were continuously implemented from 2020 to 2024. The training of both advisors and producers was carried out in accordance with the Regulations on the Annual Programme for the Development of Agricultural Advisory Services for the period covered by the study, i.e., from 2019 to 2024. Quantitative data on advisor training was collected from the Annual Reports on the Implementation of Advisor Training within the PSSS, recording the number of training events in organic production, the field of specialization, and the number of participants per training session. Qualitative and quantitative indicators of advisor training were determined through a questionnaire survey of participants (n=341), conducted after each training event (13 in total). Responses were recorded using a five-point Likert scale, from 1 (lowest) to 5 (highest). The questionnaire included the following questions: (1) How do you assess the lecture? (2) How do you assess the educational materials? (3) How do you assess the applicability of the knowledge acquired during the training? (4) How do you assess the training as a whole? Knowledge improvement was evaluated using a self-assessment test, in which participants were asked before the training: “How do you assess your level of knowledge before the training?” and after the training: “How do you assess your level of knowledge after the training?”. Knowledge improvement was expressed as a percentage and calculated as the relative difference between the initial and final self-assessment scores.

Quantitative data on producer education (number of advisory educational activities and number of participating producers), categorized by year of implementation, were collected from the Annual Reports on the Implementation of Advisory Activities – educational activities focused on organic production (lectures, panel discussions, workshops, demonstration farms, and winter schools). Standard data analysis methods were applied using Microsoft Excel.

RESULTS AND DISCUSSION

Table 1 presents the results related to the quantitative indicators of advisor training, showing the number of training modules conducted by advisor specialization and by year.

Table 1. Number of Trainings in Organic Production - Quantitative Indicators

Table 1: Number of Trainings in Organic Production - Quantitative Indicators								
Quantitative Training Parameters	Advisor Specialization							
	Crop Production			Animal Husbandry	Fruit Growing			Total
	Year of Education							Period
	2019	2021	2022*	2022	2019	2021	2022*	2019-2022
Number of Training Days	1	2	3	2	1	2	2	13
Number of Participants	23	54	98	32	23	49	62	341

* The training in 2022 also included advisors from the field of plant protection

The data in Table 1 show a gradual strengthening of educational activities for agricultural advisors, both in the number of training days delivered and in the number of participants and areas of specialization covered. Between 2019 and 2022, a total of 13 training days were held, reflecting ongoing professional support for advisors. The focus of the training topics gradually shifted from administrative to technological aspects of organic production. In the first training year (2019), the content was mainly oriented towards certification procedures, reflecting the need for advisors to acquire basic knowledge of the regulatory framework and administrative requirements of organic production. This thematic focus represents a necessary starting point for advisory work with producers considering entry into the organic production system. Subsequent training activities focused on improving standards in primary vegetable and fruit production (2021), followed by a series of trainings in 2022 addressing technologies for organic livestock production, arable-vegetable systems, and fruit and viticulture production.

The training targeted three key specializations - crop production, animal husbandry, and fruit growing with a noticeable increase in participant numbers over time, particularly in 2022, when advisors specializing in plant protection were also included. This trend indicates a growing need for an interdisciplinary approach to organic production, which is especially important given the complexity of organic farming systems that require coordinated input from multiple areas of expertise.

All advisor training activities aimed to strengthen professional capacities for transferring knowledge related to organic production. Enhancing advisors' competencies within

specific fields is a key prerequisite for effective knowledge transfer to producers and, indirectly, for increasing the adoption of organic production in Serbia. The importance of knowledge transfer in agriculture is also emphasized by Tolimir et al. (2025a), who note that agriculture in Serbia faces rapid technological change, climate-related challenges, and increasing demands for sustainable production, all of which require new learning approaches and the development of a modern knowledge base. These authors particularly highlight the role of agricultural advisory services within the Agricultural Knowledge and Innovation System (AKIS) as key intermediaries between science and practice. In the context of organic and ecological agriculture, continuous education of advisors and producers forms the foundation for effective knowledge transfer and contributes to the sustainable development of agriculture and rural areas in Serbia.

Furthermore, Gerster et al. (2024) point out that agricultural extension and advisory services (EAS) play an important role in strengthening farmers' capacities to cope with climate change and in developing sustainable production systems. These authors emphasise that viewing EAS within the AKIS framework enables more effective integration of knowledge, research, and practice, which is particularly relevant for the development of organic and ecological agriculture.

Research in EU countries shows that the Agricultural Knowledge and Innovation System (AKIS) is crucial for the modernization and sustainability of agriculture. Together with the Farm Advisory System (FAS), AKIS facilitates knowledge transfer, innovation uptake, and the exchange of experience, thereby contributing to more competitive and environmentally friendly production models (Kountios et al., 2024). Studies have shown that countries with well-developed advisory systems are more effective in promoting sustainable practices, and that continuous education of advisors and farmers forms the basis for efficient knowledge transfer and capacity building for innovation adoption. Consequently, AKIS is considered a key instrument for advancing sustainable agriculture and strengthening rural communities.

Table 2 presents data on the assessment of lecture quality, the relevance of educational materials, and the applicability of the training activities. High average scores for lectures (4.65), educational materials (4.75), and training overall (4.74) indicate that the trainings were well designed and relevant in content, that is, aligned with the needs of advisors in their work with agricultural producers. A particularly important result is the high rating of the practical applicability of the trainings, which can be linked to research showing that the practical orientation of educational activities is a key factor for successful knowledge acquisition and its application at the farm level (Röling, 2009; Rivera and Qamar, 2003). Considering the specific characteristics of organic production where technological requirements, certification procedures, and agroecological principles are often complex, the competence of advisors is of great importance, and their role as intermediaries between science and practice becomes particularly significant.

Table 2. Evaluation of Education - Quality Parameters

Table 2: Evaluation of Education Quality Parameters								
Training Quality Parameters	Advisor Specialization							All specializations average
	Crop Production			Animal Husbandry	Fruit Growing			
	Year of Education							
2019	2021	2022	2022	2019	2021	2022	2019-2022	
Lecture rating	4.20	4.75	4.88	4.95	4.20	4.71	4.85	4.65
Educational materials rating	4.55	4.78	4.88	4.90	4.55	4.77	4.85	4.75
Training applicability rating	4.86	4.88	4.97	4.95	4.84	4.74	4.88	4.87
Overall training rating	4.56	4.77	4.87	4.89	4.56	4.68	4.83	4.74

Table 3 presents the effects of advisor training in terms of knowledge improvement, based on a comparison of pre- and post-test results for all training sessions. The results indicate that the training led to clear and measurable improvements in the knowledge levels of agricultural advisors across all specializations. Overall, the average improvement in knowledge related to organic production was 38.38%, with an average pre-test score of 2.94 and a post-test score of 4.06. Based on the results achieved, it can be concluded that the implemented training programmes had a significant positive effect on improving the professional competencies of agricultural advisors, thereby creating prerequisites for the dissemination of acquired knowledge through its practical application in advisory work.

Table 3. Effects of Educations of Advisors

Year	Pre test	Post test	Knowledge Improvement (%)
Crop Production			
2019	2.90	4.0	37.93
2021	3.10	4.04	30.32
2022	2.80	4.10	46.43
Animal Husbandry			
2022	2.86	3.96	38.46
Fruit Growing			
2019	2.90	4.00	37.93
2021	2.96	4.15	40.20
2022	3.04	4.20	38.16
Average	2.94	4.06	38.38

Increasing the knowledge level of advisors enhances the quality of advisory services and enables more effective transfer of the principles of organic and sustainable production to the farm level. This is especially important in countries such as Serbia, where organic agriculture is still developing. More broadly, the results confirm that investment in advisor training is a prerequisite for achieving goals in the development of organic agriculture and

for transitioning to sustainable and environmentally friendly production systems. This further supports the view that knowledge is a fundamental resource for sustainable agriculture and long-term rural development (European Commission, 2020; FAO, 2018). Table 4 shows the results related to knowledge transfer from advisors to producers. Between 2019 and 2024, a total of 566 educational activities were conducted, involving 19,895 producers, demonstrating both the significant scale and continuity of advisory and educational work. Although there were fluctuations in the number of training activities per year, their ongoing implementation clearly reflects the existence of a stable institutional advisory framework in Serbia, which has enabled the systematic dissemination of both theoretical and practical knowledge in organic production.

Table 4. Knowledge Transfer from Advisors to Producers

Year	Number of realised activities				Number of Participants			
	Lectures and Panel Discussions	Workshop	Winter School	Total	Lectures and Panel Discussions	Workshop	Winter School	Total
2019	62	11	23	96	911	80	3112	4103
2020	52	11	22	85	705	66	2686	3457
2021	63	15	22	100	712	96	2477	3285
2022	92	12	22	126	1198	90	2427	3715
2023	64	6	22	92	900	31	2781	3712
2024	50	9	8	67	556	87	980	1623
Total	383	64	119	566	4982	450	14463	19895

According to Petrović et al. (2014), the development of organic agriculture and livestock production worldwide, in Europe, and in Serbia depends on the implementation of standards, legal regulations, and institutional support. Educational activities enable farmers to adopt organic farming practices, thereby reducing the negative impacts of intensive industrial agriculture, such as soil degradation, loss of biodiversity, and the presence of chemical residues in products. Alawa et al. (2020) emphasize the role of advisory services, noting that the integration of university-level agricultural education and advisory institutions, supported by appropriate policy initiatives, contributes to sustainable agricultural development and ecological sustainability.

Regarding the number of activities conducted, lectures and panel discussions predominate with 383 events, while winter schools (119) and workshops (64) account for a smaller share. However, when analyzed by the number of participants, winter schools contribute most significantly, with a total of 14.463 participants, highlighting their importance as an educational format. Lectures and panel discussions gathered 4.982 participants, while workshops were attended by 450 participants, which is expected given their practical and typically limited nature. It is important to note that combining theoretical and practical forms of education proved particularly significant for knowledge transfer, as it allows complementary interactions among different types of educational activities. Through lectures, panel discussions, and winter schools, a broader reach of producers was achieved, providing the transfer of fundamental knowledge on the principles of organic production, certification, and regulatory requirements. This approach is especially important in

countries where organic production is still developing, as informing producers forms the basis for decisions regarding entry into the system (Milardo, 2025).

At the same time, through workshops and activities conducted on demonstration farms, producers had the opportunity to observe the direct application of theoretical knowledge in practice, facilitating better understanding of recommended technologies and measures, and their faster and more successful adoption at the farm level. The importance of combining different forms of knowledge transfer in working with farmers has been highlighted by Cawley et al. (2023), who note that the greatest effects of knowledge transfer at the farm level are achieved by combining group and individual activities based on relevant and practically oriented content. The authors emphasise that trust among farmers, advisors, and institutions, as well as peer-to-peer learning among farmers - which in this study was represented through demonstration farms are key factors for the successful application of acquired knowledge and for achieving positive production outcomes.

Shūmane et al. (2018) underline that the integration of farmers' informal knowledge with formal knowledge systems enables the creation of more resilient and sustainable agricultural practices. Networking among farmers and multidisciplinary interactions during educational activities contribute to greater applicability of acquired knowledge and strengthen local capacities for innovation in agriculture. Simić et al. (2025) highlight that organic agriculture is an intensive and complex system, in which continuous transfer of scientific and technical information is essential for introducing innovative and sustainable solutions, particularly in plant protection and production management. These authors stress that the exchange of practical knowledge and the strengthening of ecological awareness among producers contribute to the reduction of harmful inputs, conservation of natural resources, and the development of effective agricultural knowledge and innovation systems.

CONCLUSION

The results of the research confirm that the education of agricultural advisors represents an important mechanism for the transfer of scientific knowledge in the field of organic production. The education of advisors, aimed at strengthening their competencies, was adequately designed and aligned with the modern requirements of organic production and the needs of producers, as evidenced by high ratings of quality and relevance, a significant increase in advisors' knowledge levels, and high ratings for the applicability of the acquired knowledge in practice. In the subsequent transfer of knowledge from advisors to producers, the combination of different educational formats proved to be an effective approach: lectures and winter schools enabled broad participant coverage, while workshops and demonstration activities on pilot farms contributed significantly to practical learning and knowledge application.

Further improvement of the agricultural advisory education system, accompanied by continuous adaptation of educational content to practical needs and strengthened cooperation among research institutions, advisory services, and producers, represents an important prerequisite for the long-term development of organic, sustainable, and environmentally friendly agriculture in the Republic of Serbia.

The results of this study open up space for future research, including long-term monitoring of the effects of advisor education on the adoption of production practices by producers, as well as on economic outcomes and environmental impacts. In addition, future research could focus on analyzing differences in the effectiveness of specific educational formats, regional specificities in knowledge transfer to producers, and the use of digital tools and modern information and communication technologies in advisory services.

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NATIONAL BIOECONOMY ROADMAP AS A DRIVER OF GREEN AGRIBUSINESS TRANSFORMATION

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Abstract: The Bioeconomy Roadmap of the Republic of Serbia defines a strategic framework for advancing the green transformation of agribusiness through sustainable resource use, circularity, and innovation. This paper aims to present the relevance of the Roadmap for agriculture and biomass-based value chains. The document was developed through a multi-actor co-creation process involving public institutions, research organization, industry, and civil society, utilizing analytical reviews and participatory consultations. The main results include the identification of key barriers to bioeconomy implementation, including institutional and policy gaps (limited readiness of institutions, insufficient policy support and the need for policy adjustments), knowledge and technological limitations (low awareness of bioeconomy, technological and digital constraints), and financial constraints, as well as five priority action areas: institutional strengthening, international cooperation, sustainable management of biological resources, support for circular bio-based production, and development of innovative biotechnologies. The road map provides a governance and implementation model that can enhance resource efficiency, strengthen bio-based value chains and improve resilience of the agribusiness sector. The conclusions emphasizes the need for integrated policies, targeted investments, and knowledge transfer to accelerate Serbia's transition toward a competitive, low-carbon agricultural system aligned with EU objectives.

Keywords: Bioeconomy, Circularity, Agribusiness, Biomass, Innovation

INTRODUCTION

Background and Problem Definition

Three converging pressures are reshaping agribusiness in Europe: (i) climate-change impacts on production stability and risk (heat, drought, extreme events), (ii) persistent resource inefficiency across agri-food systems (nutrient losses, residues treated as waste rather than feedstock), and (iii) continued dependence on fossil-based inputs and predominantly linear value chains (produce - process - consume - discard) (Guo et al., 2022; Beillouin et al., 2020; Lakatos and Csabai, 2025; Billen et al., 2021; Paris et al., 2022). These pressures expose structural vulnerabilities in primary production and biomass-based industries, while also increasing the policy demand for measurable decarbonisation and resource circularity across value chains (Siankwilimba et al., 2025; Lyu et al., 2024; European Commission, 2020).

Within this context, the bioeconomy is understood as the sustainable production and conversion of renewable biological resources and secondary biomass streams into food, feed, bio-based products and bioenergy, integrating circularity and low-carbon innovation across value chains (European Commission, 2018; Bugge et al., 2016). The EU's Bioeconomy Strategy positions the bioeconomy as a strategic pathway for modernising primary production systems, stimulating bio-based industrial transformation, and improving environmental performance, explicitly embedding circularity as a systemic design principle rather than an “end-of-pipe” solution (European Commission, 2025; Jander et al., 2025).

However, translating these strategic ambitions into agribusiness transformation requires operational governance tools that connect policy priorities with investment logic, stakeholder coordination, and implementable actions at sectoral and territorial levels (Kardung et al., 2021; European Commission, 2025). This is particularly critical in countries where bioeconomy policy is still emerging, institutional responsibilities remain fragmented, and cross-sectoral coordination is weak, limiting the capacity to mobilise private and public investments (Bracco et al., 2018; Ronzon and M'Barek, 2018). These conditions tend to stall uptake of bio-based innovations even when biomass potential is high (European Commission, 2025).

Policy and Scientific Relevance

At EU level, the green transformation of agribusiness is anchored in an integrated policy architecture. The European Green Deal sets the overarching framework for a transition to a climate-neutral and resource-efficient economy (European Commission, 2019). The New Circular Economy Action Plan operationalises circularity as a competitiveness agenda, prioritising systemic changes in value chains, markets, and product-policy frameworks (European Commission, 2020b). The EU Bioeconomy Strategy complements this framework by positioning the bioeconomy as a cross-sectoral transformation pathway that integrates agriculture, forestry and biomass-based industries with circularity, innovation and climate objectives, emphasising the sustainable mobilisation of biological resources, value-chain integration and measurable contributions to decarbonisation and resilience (European Commission, 2025). The Farm to Fork Strategy positions the food system, hence agriculture and biomass chains, as a core lever of sustainability, explicitly linking production practices, value-chain performance, and environmental outcomes (European Commission, 2020a).

Scientifically, this policy landscape intensifies the need for research that connects circular bioeconomy concepts to sector-specific transformation pathways in agribusiness and evaluates governance instruments that can convert broad goals into sequenced actions with accountable actors and monitoring logic. In other words, the research gap is less about whether bioeconomy and circularity matter, and more about how transition instruments are designed and deployed under real institutional, financial and coordination constraints (Hausknost et al., 2017).

For non-EU candidate countries such as Serbia, the relevance of the green transition and bioeconomy is amplified by the EU accession dynamic, as alignment with the EU acquis and Green Agenda priorities entails substantial legal and institutional obligations,

particularly under Chapter 27. A recent report highlights persistent structural weaknesses, including fragmented governance, limited administrative capacity, delayed implementation of secondary legislation, and chronic underinvestment across key domains such as waste management, water protection, climate policy, and industrial emissions control (Coalition 27, 2025). The report underscores that Serbia's primary challenge is no longer the absence of legislation, but the inability to operationalise and enforce existing rules through effective institutions, financing mechanisms, data systems, and stakeholder engagement. These governance gaps directly constrain the uptake of circular, low-carbon practices in agribusiness and biomass-based sectors, despite the country's high biological resource potential. In this context, an operational Bioeconomy Roadmap emerges as an instrument for translating environmental compliance requirements into coordinated, investment-ready actions that support structural transformation rather than just declarative alignment.

National Context of Serbia

Serbia has substantial biological-resource potential relevant for a circular bioeconomy (agriculture and forestry residues, biomass streams, and associated processing sectors), yet value addition and cascading use remain underdeveloped. The Bioeconomy Roadmap of the Republic of Serbia explicitly recognises this gap. Bioeconomy practice is at an early stage, primarily driven by sectoral initiatives rather than by a unified coordination mechanism, and it needs better data, stronger science-industry links, and more structured planning for resource streams and investments (Čule et al., 2025). This is occurring in a policy environment where energy and climate planning is being strengthened, signalling increased attention to renewables and transition investments, including areas connected to biomass and resource efficiency (Government Republic of Serbia, 2024). At the same time, broader circular-economy transition efforts supported by international partners illustrate both momentum and the continuing need for coherent governance and stakeholder coordination (Ministry of Environmental Protection of the Republic of Serbia, 2020).

Against this backdrop, the Roadmap for the Bioeconomy in the Republic of Serbia (developed within the Horizon Europe CEE2ACT project) is positioned as the first integrative, policy-support document that consolidates national priorities, identifies implementation barriers, and proposes a governance and action structure through a multi-actor co-creation process (Čule et al., 2025).

Objectives of the Paper

Building on the Roadmap for the Bioeconomy in the Republic of Serbia and its development process, this paper analyses the Roadmap as a driver of green agribusiness transformation in Serbia. Research has specific objectives to examine the Roadmap as a governance instrument, to assess its function as an operational bridge between policy, research and practice and to synthesise key barriers, priority actions and implications for agribusiness. It focuses on how the Roadmap's actions can improve resource efficiency, strengthen biomass-based value chains, and enhance the sector's resilience and competitiveness.

Although Serbia does not yet have a dedicated national bioeconomy strategy, bioeconomy principles are embedded across several strategic documents, most notably through their

integration into the upcoming Circular Economy Development Programme, where bioeconomy is recognised as a tool for linking sustainable production, processing, and consumption. In this context, the Roadmap represents the first systematic attempt to operationalise these principles by defining a shared vision, strategic goals, and priority actions for bioeconomy development. The paper therefore contributes to the literature by assessing how a bioeconomy roadmap can function as an intermediate governance instrument in accession countries, bridging strategic policy commitments and implementation capacity in the agribusiness sector.

MATERIAL AND METHODS

The study employs a qualitative, policy-oriented research design that draws on structured document analysis, comparative policy alignment, and participatory governance assessment. The primary source of analysis is the Bioeconomy Roadmap of the Republic of Serbia (Čule et al., 2025), complemented by relevant EU bioeconomy and circular economy policy frameworks, national strategic documents in agriculture, energy, forestry, and waste management, and selected outputs of the CEE2ACT project.

The analytical approach followed a multi-step framework comprising: (i) mapping bioeconomy-relevant sectors and biomass-based value chains, (ii) identification and clustering of key implementation barriers, (iii) analysis of priority action areas defined in the Roadmap, and (iv) assessment of their relevance for green agribusiness transformation. The research also draws on the multi-actor co-creation process underpinning the Roadmap, involving public administration, research institutions, industry and SMEs, and civil society, with the National Bioeconomy Hub serving as a coordination platform.

RESULTS AND DISCUSSION

Bioeconomy Roadmap as a Governance Instrument

The Bioeconomy Roadmap of the Republic of Serbia is designed as an operational governance instrument rather than a purely strategic document. It articulates a long-term vision, translates it into five strategic goals, and links these goals to a structured action framework that specifies stakeholder roles, implementation phases, financing options, and monitoring mechanisms. This structure establishes a direct link between policy objectives and implementation capacity, explicitly addressing coordination across ministries, public enterprises, local authorities, research institutions, SMEs, and civil society. The Roadmap anticipates staged delivery through short- and medium-term actions, diversified funding sources, and systematic monitoring, thereby embedding implementation logic into its design.

This governance orientation is reflected in the Roadmap's emphasis on clearly assigned responsibilities, phased implementation horizons (1-3 years and 3-5 years), mixed financing models (national budgets, EU funds, private-sector engagement and PPPs), and a defined monitoring and risk-mitigation framework, including indicators, reporting procedures, digital tools, knowledge transfer and capacity-building measures. These elements collectively distinguish the Roadmap from declarative strategy documents by operationalising coordination, sequencing, and accountability.

In contrast to existing sector-specific strategies in Serbia, such as those addressing agriculture, forestry, energy, or waste management in isolation, the Roadmap provides added value by integrating agriculture, forestry, bio-based industries, and bioenergy within a single cross-sectoral framework. This integration enables the Roadmap to function as a horizontal coordination tool that aligns sectoral policies with green transition objectives and EU bioeconomy and circular economy agendas, while offering a shared reference point for agribusiness transformation across value chains.

From a comparative perspective, analysis of the CEE2ACT national roadmaps shows that three governance features are standard across countries: (i) bottom-up coordination through national bioeconomy hubs, (ii) action-oriented planning with indicative timelines, and (iii) initial development of monitoring and indicator frameworks (CEE2ACT Project, 2025). However, countries differ significantly in institutional maturity, policy anchoring, and proximity to a formal national bioeconomy strategy.

Within this comparative context, Serbia's Bioeconomy Roadmap places stronger emphasis on operational governance and implementation logic than many other CEE roadmaps. While roadmaps in countries such as Bulgaria and Romania predominantly outline thematic priorities and sectoral opportunities, the Serbian Roadmap more explicitly links strategic objectives to defined action areas, responsible actors, and coordination mechanisms, reflecting a response to persistent national governance fragmentation. Unlike several CEE counterparts, where bioeconomy policy remains embedded within sector-specific strategies, the Serbian Roadmap adopts a genuinely cross-sectoral governance approach, positioning agriculture, forestry, biomass residues, and bioenergy within a unified framework. This positioning highlights its role as a policy-bridging instrument tailored to contexts with high biomass potential but limited implementation capacity, where enforceable and sequenced actions are more critical than vision alignment alone.

Identified Barriers to Bioeconomy Implementation in Serbia

The Roadmap identifies a set of interrelated barriers that constrain the effective implementation of bioeconomy principles and the transformation of agribusiness and biomass-based value chains. These barriers are grouped into three categories: institutional and policy barriers, knowledge and technological barriers, and financial and market barriers.

Institutional and policy barriers emerge as the most critical constraints. The Roadmap highlights limited institutional readiness for coordinated bioeconomy governance, weak integration of bioeconomy objectives into sectoral policies, and insufficient inter-ministerial coordination across agriculture, forestry, energy, environment, and innovation portfolios. The absence of a dedicated operational framework and clearly assigned responsibilities further undermines policy coherence, despite the existence of multiple relevant strategic documents at the national level.

Knowledge and technological barriers are linked to low awareness and limited understanding of bioeconomy concepts among public authorities, producers, and SMEs. The Roadmap points to insufficient knowledge dissemination, weak science-industry linkages, and limited uptake of digital tools and advanced bio-based technologies in

agriculture and biomass processing. These gaps reduce the capacity for innovation and constrain the scaling-up of circular and bio-based solutions.

Financial and market barriers include restricted access to targeted financing instruments, underdeveloped incentives for bio-based investments, and high perceived risks associated with innovative bioeconomy projects. Fragmented and short-term funding mechanisms, often poorly aligned with bioeconomy priorities, discourage private-sector engagement and slow market development, particularly for SMEs.

When placed in a comparative CEE context, the barriers identified in Serbia largely mirror those reported in Bulgaria, Romania, Slovakia, and Hungary, where fragmented governance, limited coordination, insufficient awareness, and constrained financing are recurrent challenges (CEE2ACT Project, 2025). However, Serbia is characterised by more pronounced gaps between strategic intent and operational capacity, reflecting accession-related pressures and delayed translation of policy commitments into concrete instruments.

EU-level bioeconomy assessments reinforce this interpretation, showing that although many CEE countries possess substantial biomass potential, the absence of integrated governance structures, stable financing, and effective knowledge-transfer mechanisms remains a systemic obstacle (European Commission, 2018; 2025). In this context, the Serbian Bioeconomy Roadmap responds directly to these constraints by explicitly identifying barriers and linking them to priority action areas, thereby enabling a shift from declarative alignment toward implementable and measurable pathways for agribusiness transformation.

Priority Action Areas and Relevance for Agribusiness

The vision of the Bioeconomy Roadmap of the Republic of Serbia is centred on efficient, rational, and responsible resource use grounded in circular bioeconomy principles. It emphasises waste prevention, valorisation of residues and by-products, investment incentives, and the creation of added value with minimal environmental impact (Čule et al., 2025). Agribusiness is positioned as a core pillar of this transition, reflecting its dual role as a primary biomass provider and a key beneficiary of bioeconomy development.

The first priority action area, institutional capacity-building and policy support, focuses on establishing a coherent strategic, legislative, and institutional framework supported by incentive mechanisms and targeted capacity-building. By strengthening human and organisational capacities and improving cross-sectoral coordination, this action area addresses fragmented governance and creates more predictable conditions for bio-based investments. For farmers and agri-SMEs, this translates into clearer regulatory settings, reduced administrative uncertainty, and improved access to harmonised support schemes.

The second action area, international and regional cooperation, supports Serbia's integration into European bioeconomy networks, research initiatives, and markets. For agribusiness and biomass processors, this facilitates technology transfer, market access, and compliance with EU sustainability standards, while also enabling knowledge exchange and joint value-chain development in rural and cross-border regions.

The third action area, sustainable management of biological resources, is directly linked to agribusiness performance and resilience. It promotes improved land, forest, and biomass management practices that enhance productivity while safeguarding ecosystems. For farmers and rural communities, this supports diversification, sustainable intensification, and increased retention of local value, particularly through the use of agricultural and forestry residues.

The fourth action area, support for circular bio-based production and value chains, represents the most direct lever for agribusiness transformation. By prioritising cascading biomass use and waste-to-resource models, it creates new income streams for farmers, strengthens agri-SMEs involved in processing and logistics, and stimulates rural employment by anchoring value addition closer to biomass sources.

The fifth action area, development of innovative biotechnologies and circular solutions, focuses on research, demonstration, and market uptake. A key emphasis is placed on public–private partnerships, which facilitate cooperation between research institutions, public authorities, and industry. For agribusiness, this includes biotechnologies for sustainable inputs, bio-based materials, and precision and digital applications that improve resource efficiency. Pilot projects, living labs, and stronger research–industry linkages are particularly relevant for innovation-oriented agri-SMEs and start-ups.

Compared with other CEE roadmaps, Serbia's Roadmap prioritises governance coordination, sustainable resource management, and circular value chains (CEE2ACT Project, 2025). However, it places stronger emphasis on operationalisation and implementation mechanisms, reflecting national accession-related constraints and enforcement gaps. This focus on agribusiness actors and rural development needs reinforces the Roadmap's role as an implementation-oriented policy framework rather than a purely strategic vision.

Implications for Green Agribusiness Transformation

The Bioeconomy Roadmap sends a clear strategic signal to shift Serbian agribusiness from primary production toward higher-value, bio-based value chains. By promoting cascading biomass use, bio-based products, and integration with forestry, energy, and bio-processing sectors, it enables farmers, agri-SMEs, and processors to capture greater value along the chain (Čule et al., 2025).

A central implication is improved resource efficiency, particularly through systematic utilisation of residues and by-products. Circular approaches reduce losses, close nutrient loops, and support sustainable input use, thereby lowering environmental pressures while improving cost efficiency and regulatory compliance, issues of particular importance for small and medium agribusinesses (Swastika, 2024; Behera, 2025).

The governance and support framework also strengthens agribusiness resilience and competitiveness by encouraging innovation, income diversification, and adoption of bio-based and digital solutions. Evidence from other CEE countries shows that coordinated bioeconomy policies can support rural development, agri-SMEs, and long-term adaptability to climate and market risks (CEE2ACT Project, 2025).

Finally, the Roadmap facilitates alignment with EU sustainability, climate, and circular bioeconomy objectives (European Commission, 2019, 2020a,b, 2025). By translating EU-level ambitions into nationally tailored, operational actions, it supports gradual convergence while addressing domestic structural constraints. In this sense, the Roadmap serves as both a strategic and a practical transition tool to advance green agribusiness transformation in Serbia.

CONCLUSION

The Bioeconomy Roadmap of the Republic of Serbia represents a practical policy-support tool that moves beyond strategic declarations by providing a structured framework for coordinating policies, actors, and investments relevant to the green transformation of agribusiness. By explicitly linking bioeconomy objectives with agriculture, forestry, biomass processing, and rural development, the Roadmap acts as a catalyst for agribusiness transformation, encouraging the shift from primary production toward value-added, circular bio-based value chains. At the same time, it lays a foundation for the future development of a comprehensive national bioeconomy strategy, offering tested governance logic, priority action areas, and implementation pathways.

The analysis highlights several key success factors for effective implementation. An integrated policy approach is essential to overcome sectoral fragmentation and ensure coherence across agriculture, energy, environment, innovation, and rural development policies. Targeted investments, supported by predictable financing instruments and incentives, are required to enable farmers, agri-SMEs, and biomass processors to adopt bio-based innovations and circular practices. Equally important is systematic knowledge transfer, including capacity-building, stakeholder engagement, and stronger links between research, industry, and public administration, which together enable the translation of policy goals into operational outcomes.

Without timely and coordinated implementation, the Roadmap risks remaining a declarative document, sustaining existing gaps between policy ambition and on-the-ground transformation in agribusiness and rural areas. Looking ahead, priority next steps include the gradual institutionalisation of the Roadmap through monitoring milestones, financing mechanisms, and stakeholder governance structures, as well as its evolution toward a formal national bioeconomy strategy aligned with EU transition objectives. Beyond its national relevance, the Serbian Bioeconomy Roadmap offers broader applicability to other Western Balkan and CEE countries facing similar challenges, providing a transferable model for bridging policy ambition and implementation capacity in support of greener, more resilient, and more competitive agribusiness systems.

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INFLUENCE OF NPK REGIMES ON WHEAT AGRONOMIC AND SOIL MICROBIOLOGICAL PARAMETERS

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Abstract: Wheat agronomic traits and soil microbial activity were closely shaped by NPK supply. Moderate to high fertilization improved plant height, thousand grain weight and yield, while the number of grains per spike remained relatively stable. Number of *Azotobacter* spp. and soil dehydrogenase activity increased with nutrient input, ammonifiers increased mainly at higher rates, and actinomycetes did not change significantly. Statistical results confirm the importance of balanced NPK management for enhancing both wheat productivity and soil biology.

Keywords: Agronomic traits, *Triticum aestivum* L., DHA

INTRODUCTION

Wheat is one of the most extensively cultivated cereal crops globally, occupying a substantial share of agricultural land and serving as a cornerstone of global food production. According to recent estimates by the Food and Agriculture Organization (FAO), wheat has grown to nearly 220 million hectares worldwide, with a total annual output of approximately 779 million tons in 2023 (Murindangabo et al., 2025). These global patterns are translated to the regional scale. For instance, in the Republic of Serbia wheat production in 2023 reached 3.449 million tons, representing a 10.9% increase compared to the previous year, while the total sown area amounted to 682.246 ha (Dolijanović et al., 2025). Together, these figures highlight the strategic importance of wheat in national agriculture and its broader contribution to regional and global food security. Wheat has important role in human nutrition as the primary cereal that feeds over 50% of the world's population (Erenstein et al., 2022). Wheat grain is energy source, rich in carbohydrates like starch, and is also a significant source of protein, lipids, minerals, and fiber (Khalid et al., 2023). The quality and yield of wheat grain are influenced by numerous factors, including the wheat genotype, production conditions such as climate, the soil's physicochemical and biological characteristics, and the type of agricultural production (Filip et al., 2023). These factors determine the economic viability of wheat cultivation and impact food quality and safety which are key elements of sustainable economic and societal development (Durham and Mizik, 2021). Throughout the growing season, winter wheat exhibits substantial demands for mineral nutrients, especially nitrogen, which has the greatest impact on productivity (Hou et al., 2025). However, excessive nitrogen application can decrease yield and

contribute to agroecosystem pollution. Moreover, fertilizer use efficiency and final yield formation are strongly affected by weather conditions during the season and the specific characteristics of the production site (Liu et al., 2021). While synthetic NPK fertilization is widely adopted to enhance crop performance, its consequences for the soil biological community remain a critical research focus. Unbalanced or increased NPK inputs can affect natural nutrient cycling and suppress key functional groups of microorganisms, including nitrogen-fixing and phosphate-solubilizing bacteria. Assessing how different NPK doses influence soil biogenicity is essential for understanding nutrient-use efficiency and for identifying potential threats to long-term soil health, such as interrupting soil structure or reduced ecological resilience (Rai and Sarkar, 2025).

This work has been carried out to examine how wheat morphological and productive parameters and related soil microbial communities are influenced by different nutrient regimes, particularly nitrogen (N), phosphorus (P) and potassium (K). The analysis focuses on plant height, number of grains per spike, thousand-grain weight, and grain yield. The response of selected soil microbial activity indicators was also evaluated under field conditions.

MATERIAL AND METHODS

Experimental Site Description

Field experiments were conducted at an experimental station in the Research and Development Institute Tamiš, Pančevo, Serbia (44°56'23.395", 20°43'27.328") in 2022/23 growing season. Agrochemical analyses of the experimental field indicated that the soil type was chernozem, and it was characterized by an alkaline reaction. The content of calcium carbonate (CaCO_3) was moderate, and the soil was well supplied with humus. Total nitrogen content was stable, while the amount of readily available phosphorus (P_2O_5) indicated moderate to optimal availability. However, readily available potassium (K_2O) was found at high levels. During the 2022/2023 growing season, the total amount of precipitation was above the long-term average, while mean temperatures throughout the season were consistently higher than normal for this time of year.

Experimental Design

The experiment was arranged as a randomized complete block design with three replications. Six NPK regimes were included in the experiment, with each experimental plot measures 10x10 m (20 rows) (Table 1). An examination was carried out on a winter variety of common wheat, Apilco. Fertilization with all NPK mineral fertilizer treatments was performed manually by plots in the autumn, followed immediately by basic conservation tillage using a disc harrow (TO36/610). Pre-sowing soil preparation was conducted with a heavy harrow, while sowing was carried out mechanically using a seed drill. Fertilization with all NPK treatments was applied on 02 October 2022 (Table 1). Conservation tillage was carried out on 04 October 2022, followed by pre-sowing soil preparation on 14 October 2022. Sowing was performed on 21 October 2022. The first chemical protection treatment took place on 10 April 2023, and the second on 11 May 2023. Harvest was conducted on 11 July 2023. The seeding rate was 210 kg ha⁻¹. The first chemical treatment was applied using Lodin (0.6 L ha⁻¹) + Tezis (10 g ha⁻¹) + Savate CS

(0.2 L ha⁻¹), in the phase BBCH 47, to suppress *Lema melanopus*, *Erysiphe Graminis*, *Septoria* spp., and *Puccinia* spp. The second chemical treatment involved Ison (0.6 L ha⁻¹) + Polux (0.3 L ha⁻¹) (Table 2). Harvesting was performed with plot combines for harvesting, at the stage of physiological maturity when the grain moisture was below 14%.

Table 1. Fertilization treatments used in wheat experiments (kg ha⁻¹).

Treatment number	NPK treatment		
	C	N-0	P-0
T1		N-50	P-50
T2		N-100	P-50
T3		N-100	P-100
T4		N-130	P-50
T5		N-130	P-130

Morphological and Productive Traits Analysis

At the full maturity stage of wheat, about ten days before harvest, whole-plant samples were collected across all variants, in three replications, to study: plant height (PH), number of grains per spike (NGS), thousand-grain weight (TGW, g) and grain yield (t/ha). The samples were taken to the laboratory, the grains were separated from the husk, manually counted for each spike, and their grain weight per spike was measured using an analytical balance. Grain yields were measured for each variant and replication and converted into tons per hectare, based on 14% grain moisture.

Microbiological Soil Analyses

Soil samples for microbiological analyses were collected from the rhizosphere zone of wheat at a depth of 0-10 cm. During each sampling, disposable gloves were used, and all equipment (spade and mixing tray) was disinfected with 70% ethanol prior to contact with soil. Composite samples were obtained by homogenizing multiple subsamples collected within each plot. A representative portion of the composite sample was immediately transferred into sterile, labeled polyethylene bags and transported under cold conditions to the laboratory. Microbiological analyses, were performed within 24 h of collection, as explained in Racić et al. (2017). Shortly, the colony-forming units (CFUs) of the numbers of ammonifiers (AMO), *Azotobacter* spp. (AZO), actinomycete (ACT) were determined by serial dilution and plating on selective media. The number of AZOs on nitrogen-free medium using the fertile drops method, the number of AMO on meat pepton agar (MPA), and actinomycete on synthetic medium. Incubation temperature was 28 °C, while the incubation time depended on the tested group of microorganisms. Soil was dried at 105 °C for 2 h, and the number of microorganisms was estimated as CFU g⁻¹ dry weight (DW). DHA was measured spectrophotometrically by the modified method according to Thalmann and expressed as µg TPF g⁻¹ soil (triphenylformazan g⁻¹ soil). All measurements were performed in three replicates.

Statistical Analysis

Prior to statistical analysis, data were tested for normality using the Shapiro-Wilk test. All variables showed a normal distribution. Differences among NPK fertilization treatments

were evaluated using one-way ANOVA, and mean comparisons were performed using Tukey's post hoc test at a significance level of $p \leq 0.05$. Statistical analyses were conducted using SPSS software (version 27, IBM Corp., USA). Pearson correlation analysis was applied to assess relationships between agronomic traits and microbiological parameters. Principal component analysis (PCA) was used to explore multivariate relationships among treatments and was performed using Python (Python Software Foundation, Wilmington, USA).

RESULTS AND DISCUSSION

The applied NPK regimes had significant effects on most of the agronomic and microbiological parameters of wheat. PH, NGS, TGW, and yield varied across treatments, which accompanied the changes recorded for the number of microbial groups investigated and DHA. PH, NGS, and TGW significantly differed between applied nutrient regimes (Table 2). The tallest plants were recorded in T2 (82.53 cm), followed by T4 and T5, treatments with higher doses of nutrient inputs, whereas the shortest plants were observed in C and T1 (≈ 72 to 73 cm). Similar trends were evident for yield components: the higher NGS (2.18 grains spike⁻¹) and TGW (46.97 g) were determined in T2, while T1 had the lowest values for both traits. These responses correspond to earlier findings demonstrating that mineral fertilization significantly increases plant height, spike fertility, and grain weight in wheat (Amjadian et al., 2021; Ivanova et al., 2024). Also, Irfan et al. (2018) demonstrated similar effects, reporting linear increases in plant height, NGS, and 100-grain weight with rising N-P₂O₅ rates, with the highest values recorded at 150-110 kg N-P₂O₅ ha⁻¹.

Table 2. Effect of different NPK fertilization treatments on wheat agronomic traits.

	PH (cm)	NGS	TGW (g)
C	72.67±4.64 ^c	1.77 ± 0.61 ^{ab}	43.56 ± 8.66 ^{bc}
T1	72.6±7.58 ^{bc}	1.54 ± 0.68 ^b	37.63 ± 9.72 ^c
T2	82.53±4.52 ^{ab}	2.18 ± 0.67 ^a	46.97 ± 8.45 ^a
T3	77.03 ± 13.34 ^{abc}	1.804 ± 0.72 ^{ab}	42.79 ± 9.86 ^{abc}
T4	80.63 ± 6.13 ^{ab}	1.91 ± 0.67 ^{ab}	42.23 ± 8.05 ^{abc}
T5	82.37 ± 4.68 ^{ab}	1.86 ± 0.47 ^{ab}	43.82 ± 8.12 ^{ab}

Values represent mean ± standard deviation. Different letters within a column indicate statistically significant differences according to Tukey's test ($p \leq 0.05$).

Wheat yield varied significantly among the applied regimes of NPK, with the lowest values in C (3.91 t ha⁻¹) and T1 (4.13 t ha⁻¹). Significant increases were determined for T2 and T3, for $\approx 30\%$ in comparison to the control. However, the highest yields were recorded for T4 and T5, for $\approx 55\%$ in comparison to the control (Table 3). Similar yield responses of wheat to increasing mineral fertilization have been reported in other studies, where high NPK rates (175-150-125kg N-P-Kha⁻¹) increased grain yield by 50-60% over unfertilized plots, and moderate NP fertilization produced yield gains of roughly 30% compared with the control (Malghani et al., 2010; Samimi et al., 2016; Rusek et al., 2016). As only one genotype was used in our experiment, the observed variability in yield can be attributed primarily to differences in nutrient supply, which is consistent with factorial NPK experiments on single wheat genotypes showing significantly higher yields (≈ 6.3 to 6.6 t

ha⁻¹) at optimal NPK combinations compared with lower fertilization levels (Rawal et al., 2022).

Table 3. Grain yield of wheat varieties under different NPK fertilization treatments.

YIELD (t ha ⁻¹)	
C	3.91±0.3 ^c
T1	4.13±0.44 ^c
T2	5.55±0.27 ^b
T3	5.74±0.22 ^b
T4	6.96±0.29 ^a
T5	6.81±0.23 ^a

Values represent mean ± standard deviation. Different letters within a column indicate statistically significant differences according to Tukey's test ($p \leq 0.05$).

Table 4. Effect of different NPK fertilization treatments on soil microbial parameters.

	AZO (CFU ×10 ³ g ⁻¹)	AMO (CFU ×10 ³ g ⁻¹)	ACT (CFU ×10 ³ g ⁻¹)	DHA (μg TPF g ⁻¹ h ⁻¹)
C	167.17±10.63 ^{cd}	266.27±3.66 ^a	26.35±5.88 ^a	13.90±0.10 ^b
T1	231.85±3.55 ^a	275.81±33.91 ^a	14.37±1.36 ^a	14.33±0.68 ^b
T2	194.46±8.15 ^{bc}	313.97±30.03 ^a	27.19±2.25 ^a	22.3±1.25 ^a
T3	231.15±25.65 ^a	190.07±4.05 ^b	21.40±8.21 ^a	22.03±0.31 ^a
T4	149.70±1.82 ^d	286.17±1.38 ^a	18.09±4.09 ^a	23.53±3.21 ^a
T5	223.67±12.07 ^{ab}	264.70±10.90 ^a	28.75±8.15 ^a	24.03±1.75 ^a

Values represent mean ± standard deviation. Different letters within a column indicate statistically significant differences according to Tukey's test ($p \leq 0.05$).

Differences among the varieties influenced the examined microbiological parameters, including numbers of AZO, AMO, ACT, and DHA (Table 4). Our results are in accordance with a global meta-analysis by Geisseler and Scow (2014), who showed that mineral fertilization increases microbial biomass carbon by an average of 15.1%. Likewise, Allison and Martiny (2008) demonstrated that the composition of microbial communities responds sensitively to the rates of N, P, and K application. In our experiment, number of *Azotobacter* spp. ranged from 149.70×10³ to 231.85×10³ CFU g⁻¹, with the highest values recorded in T1 and significantly lower numbers in T4. The significant increase of 22% in comparison to the control was determined for T5. Similarly, number of AZO under fertilized conditions have been reported in sugar beet and other arable crops, where NPK combined with organic inputs maintained or slightly stimulated AZO compared to unfertilized controls (Mrkovački et al., 2003; Shrestha et al., 2025). The highest AMO counts were recorded in T2 (313.97 CFU ×10³ g⁻¹), followed by C, T1, T4 and T5, which showed comparable values. The lowest AMO measurement was observed in T3 (190.07 CFU ×10³ g⁻¹). Roljević-Nikolić et al. (2022) found that AMO number is on average 119.3 ×10³ to ×10⁵ g⁻¹ depending on fertilization and wheat subspecies, with organic and biofertilizer treatments increasing ammonifier number up to 56% relative to controls. These trends align with our observation that T2 showed significantly higher AMO counts than T3, suggesting that fertilization regime and soil conditions modulate ammonifier populations in wheat systems. ACT number ranged from 14.37 to 28.75 CFU ×10³ g⁻¹. The highest ACT value was measured

in T5 while the lowest was found in T1. These findings are consistent with the results reported by Li et al. (2022), who showed that actinomycetes, fungi, bacterial PLFA contents, and total PLFAs increased under P fertilization (NP and NPK) compared with unfertilized control samples. DHA activity significantly differed among treatments. The analysis of the DHA activity showed clear differences among the examined variants. The greatest DHA values were recorded in T5, followed by T2, T3 and T4. Significantly lower enzyme activity was detected in control and T1. The treatment which showed the highest DHA value corresponded to the treatment with the largest dose of NPK applied (N₁₃₀P₁₃₀K₁₃₀), where the activity increased by 57.84% compared with the control. Our results are consistent with the findings of Roljević-Nikolić et al. (2022) that fertilization treatments significantly enhance microbial functional activity in the rhizosphere. Akmal et al. (2012), reported that the NP fertilizer treatment led to a 22.0% higher dehydrogenase activity compared to the unfertilized control. Moreover, Dhiman et al. (2019) reported the highest DHA value (44.1 µg TPF g⁻¹ soil 24 h⁻¹) in plots receiving 100% NPK together with farmyard manure in the surface layer, indicating that combined nutrient and organic inputs can enhance microbial oxidative activity more strongly than mineral fertilization alone. These findings correspond with long-term studies showing that NPK fertilization enhances microbial activity and enzymatic functioning (Guo et al., 2020). The observed responses of *Azotobacter* and actinomycetes also reflect the microbial behaviour described by Kaur et al. (2017), who concluded that enhanced microbial activity and improved plant growth under enriched nutrient conditions.

The correlation matrix showed different relationships between agronomic parameters and microbiological indicators. TGW and the NGS showed a strong positive correlation (r = 0.91), confirming results of Minov et al. (2024) found highly positive correlations between the weight of grains per spike and the number of grains per spike (r = 0.852), as well as between grain yield and TGW (r = 0.928) and NGS (r = 0.793) in wheat field trials, confirming that increases in both TGW and NGS are associated with improved yield potential. YLD showed a strong association with DHA (r = 0.88), suggesting that increased microbial oxidative activity contributed to improved grain formation. PH had positive correlations with TGW (r = 0.57), YLD (r = 0.59) and DHA (r = 0.66), indicating that taller plants generally produced heavier grains and higher yields. Actinomycetes showed moderate correlations with NGS and TGW, whereas *Azotobacter* spp. had weak associations with agronomic parameters. These relations are in line with earlier studies reporting that enzymatic activity and nitrogen-transforming microbial populations are important indicators of soil fertility and crop productivity (Guo et al., 2020; Wang et al., 2023).



Figure 1. Heatmap of Pearson correlation coefficient (r) among wheat agronomic traits and soil microbial parameters

The PCA based on PH, NGS, TGW, and YLD explained a substantial proportion of total variability (with a cumulative total of 89.7%; PC1 = 62.3%; PC2 = 27.4%) (Figure 2). Treatments T4 and T5 were grouped in the positive part of the diagram, closely aligned with YLD and PH vectors. This indicates that these variants combined positive contributions from multiple YLD components. Treatments C and T1 were positioned in the opposite quadrant, reflecting their lower values for all agronomic traits. The TGW and NGS vectors were closely aligned, supporting their strong correlation and shared contribution to yield formation.

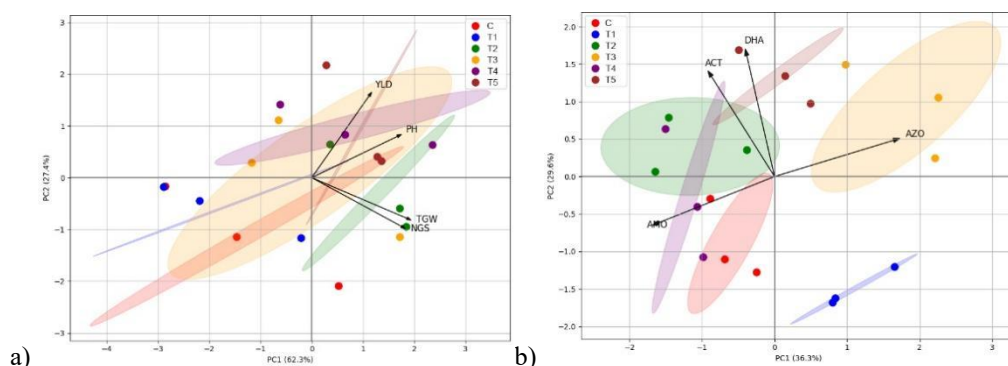


Figure 2. **a)** Principal component analysis (PCA) of wheat agronomic traits (PH, NGS, TGW, yield) under different NPK fertilization treatments. **b)** Principal component analysis (PCA) of soil microbial parameters (AZO, AMO, ACT, DHA) under different NPK fertilization treatments.

The PCA including AZO, AMO, ACT and DHA accounted for 65.9% of total variability (PC1 = 36.3%; PC2 = 29.6%). Treatments T2, T4, and T5 were positioned near the DHA and actinomycetes vector, corresponding to their higher enzymatic and microbial activity. T3 were associated more closely with *Azotobacter* spp. number, while. treatments C and T1 were grouped together in the region reflecting low microbial activity, particularly for DHA and actinomycetes. These findings align with long-term fertilization studies indicating that microbial abundance and enzyme activity are strongly influenced by nutrient regimes (Guo et al., 2020; Li et al., 2022).

When agronomic and microbiological indicators were jointly analyzed, treatments formed three distinct groups. T4 and T5 were positioned in the quadrant associated with higher values of grain yield, plant height, and DHA indicating a positive interaction between soil biological activity and crop performance. T2 and T3 formed an intermediate group with average values for both agronomic and microbiological parameters. C and T1 were grouped in the area associated with lower values for most parameters. These clusters reflect the integrated influence of NPK fertilization on plant performance and soil microbial functioning, which is also confirmed in the literature (Amjadian et al., 2021; Mikos-Szymańska et al., 2018).

CONCLUSION

Our results demonstrate that while moderate fertilization substantially improves several agronomic traits, higher nutrient inputs are required to maximize yield and stimulate soil microbial activity. The combined ANOVA and Tukey test results confirm the importance

of balanced NPK management for enhancing both wheat productivity and soil biology, with implications for sustainable nutrient management in wheat-based cropping system.

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AMBROSIA ARTEMISIIFOLIA AS A PUBLIC HEALTH CONCERN

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Abstract: *Ambrosia artemisiifolia* (ragweed) is an annual broadleaf plant native to North America, in the Europe it was introduced in the second half of the 19th century with the potatoes and seeds of wheat and red clover. Ragweed is an invasive weed species and one of the most important causes of seasonal allergies in Europe, including the Balkan region. Due to its highly allergenic pollen, it has a significant public health concern. A single plant can produce billions of pollen grains, and allergic symptoms may occur even at very low pollen concentrations. Ragweed flowers from August to October, with peak flowering in late summer, and its pollen is readily dispersed by wind over long distances. Pollen of ragweed can cause a range of adverse health effects in sensitized individuals, including allergic rhinitis (nasal congestion, rhinorrhea, and sneezing), allergic conjunctivitis (eye redness, tearing, and burning), exacerbation of asthma symptoms, and a reduced quality of life manifested by fatigue, sleep disturbances, and decreased work and school productivity). Allergic diseases have substantial public health implications, including increased healthcare costs (medications and medical examinations), higher rates of absenteeism from work and school, and an increased burden on healthcare systems during the allergy season. Public health is defined as a set of knowledge, skills, and activities aimed at promoting health, preventing and controlling disease, and prolonging and improving quality of life through organized societal measures. The public health system comprises the structures and processes that create conditions for the preservation and improvement of population health through the activities of public health stakeholders. These stakeholders include, among others, local government units, public media, companies, public enterprises, entrepreneurs, and citizens. Given the fact that ragweed pollen causes a serious health risk, which is further exacerbated by ongoing climate change, regular and systematic monitoring of ragweed occurrence and control is essential. Community-level prevention and management measures include the systematic removal of ragweed before flowering (e.g., uprooting and mowing), maintenance of neglected areas (such as construction sites, roadsides, and agricultural land), public education and engagement of local communities in preventing the spread and ensuring timely control of ragweed, and the development of legislation obligating landowners to implement control measures.

Keywords: Ragweed, Public health, Control

INTRODUCTION

General Characteristics of Weed Species *Ambrosia artemisiifolia* L.

Ragweed is an annual invasive weed from the family *Asteraceae* (Compositae). Originated from the southern desert regions of North America, spread to Europe and Asia in the late 19th and early 20th centuries. In Europe, its main areas of distribution is France, Ukraine

and northern Italy the Pannonian Basin, particularly Hungary, Serbia, Croatia, Slovakia (Sikoparija et al., 2017), as a Bosnia and Herzegovina (Trkulja et al., 2015). In last decades, a northward shift in the species' distribution range has been observed (Grewling, 2016). International trade and climate change are considered key drivers of ragweed invasion (Sikoparija et al., 2017). Ragweed exhibits all the characteristics of an invasive plant: it efficiently exploits environmental resources, tolerates extreme environmental conditions, and displays pronounced genetic plasticity due to the presence of numerous ecotypes, enabling rapid spread and invasive expansion (Buttenschön et al., 2010).

Ragweed is an annual herbaceous plant that survives unfavorable periods of the year in the form of seeds; it is classified as a therophyte and reproduces exclusively by seed. Seeds can persist in the soil for up to 40 years. Approximately 85% of seeds retained their germination capacity after 20 years of burial; however, in shorter-term experiments lasting two to three years, annual seed mortality rates of 7 and 12% were recorded (Charles et al., 2021). Ragweed plants grow particularly well in abandoned, degraded, and disturbed soils resulting from human activities and deforestation (Albertini et al., 2022). Seed production varies with plant size, population density, and habitat characteristics, with plants growing at lower densities producing more seeds than those in dense stands. In a study of several ragweed populations in France, seed production per plant ranged from 346 to 6.114, with an average of approximately 2.500 seeds per plant (Buttenschön et al., 2010). Ragweed germinates early in spring and exhibits rapid growth, showing strong competitiveness at early developmental stages. Plant height can range from 30 cm to 2 m and is strongly influenced by air temperature, soil fertility, soil moisture availability, and competition from other plants. Ragweed can germinate within small-grain crops and remain in a juvenile stage until harvest; once exposed to light, it resumes rapid growth. The species is adapted to well-illuminated sites and slightly acidic, nutrient-rich soils, but it is also tolerant of drought (Buttenschön et al., 2010). Vučković et al., (2011) reported a high abundance of ragweed seeds in soil under maize cultivation. At a soil depth of 0-10 cm, 2.813 seeds m⁻² were recorded; at 10-20 cm, seed density was 2.343 seeds m⁻²; and at 20-30 cm, 313 seeds m⁻². Consequently, the total abundance of ragweed seeds in the plough layer reached up to 5.469 seeds m⁻².

Ragweed is a monoecious plant species with numerous, small flowers arranged in unisexual capitate inflorescences. The male inflorescences are hemispherical and pendulous, containing a larger number of flowers (10-15) and are aggregated into dense, terminally positioned racemose inflorescences. The female inflorescences consist of single flowers enclosed within a corolla and are located below the male inflorescences in the axils of the upper leaves (Bonnot, 1967; Wayne et al., 2002, cited in Vrbničanin, 2015). This floral arrangement results in the production of a disproportionately large number of pollen grains relative to the number of ovaries (gynoecia).

It is a short-day plant. In Central Europe, plants usually flower from July to October, with seed production beginning in mid-August. The relatively late flowering and seed maturation limit the species' distribution into more northern climatic zones. However, temperature changes over the past 30 years have resulted in an extended growing season by approximately 8-10 days in Germany thereby enabling ragweed to expand northward and to higher altitudes (Buttenschön et al., 2010).

Production and Atmospheric Distribution of Ragweed Pollen

Ragweed poses a significant public health problem due to its anemophilous and highly allergenic pollen (Albertini et al., 2022). More than 50% of pollen-induced allergic reactions are attributed to ragweed pollen (Frenz, 1999; D'Amato et al., 1998, cited in Janjić and Lazić, 2015). Ragweed pollen production is commonly expressed as the number of pollen grains per m^3 of air (P m^{-3}), either on a daily basis or as the total annual pollen load. The clinical threshold concentration for allergic symptoms is approximately 30 pollen grains m^{-3} . Trkulja et al. (2010) reported, based on a seven-year monitoring period (2007-2013) in the city of Banja Luka, that the total annual pollen counts were 8.669 P m^{-3} in 2007, 5.841 P m^{-3} in 2008, 4.084 P m^{-3} in 2009, 7.045 P m^{-3} in 2010, 9.587 P m^{-3} in 2011, 8.993 P m^{-3} in 2012, and 5.004 P m^{-3} in 2013. In the research Šikoparija et al. (2018) during three flowering seasons in the Pannonian part of Serbia (2014-2016), pollen production per day ranged from 6.38 billion to 770 billion pollen grains for the experimental field (10 m×10 m patch with soil from a heavily infested agriculture area). Ragweed pollen can be transported over long distances (long-distance transport, LDT), even across thousands of kilometers, and this phenomenon has been observed in many European countries. Numerous studies indicate that ragweed pollen grains have the potential to trigger allergic reactions not only in areas with high ragweed abundance but also in regions where ragweed populations are absent or scarce (Grewling et al., 2017). Research by de Weger et al. (2016) as a Weryszko-Chmielewska and Piotrowska (2008) show that, under favorable atmospheric conditions, ragweed pollen released from the Pannonian Plain can be lifted into higher atmospheric layers and entrained in air masses moving toward northwestern Europe, where the pollen subsequently deposits to the ground. Research by Celenk and Malyer (2017) showed that ragweed pollen grains in Bursa (Turkey) did not originate from local sources but were transported over long distances from potential source regions around the Sea of Azov in Russia and Ukraine, as well as from the Black Sea region in Turkey, Romania, and Bulgaria. Damialis et al. (2005) investigated the abundance of weed pollen grains, including ragweed, in relation to wind direction, speed, and persistence. The distance traveled by pollen after its release into the atmosphere is closely associated with wind as a vector. Damialis et al. (2005) investigated the effects of wind direction, speed, and duration (persistence) on the transport of the 12 most abundant pollen taxa in Thessaloniki. For most of the studied plant taxa, amount of airborne pollen was correlated either with wind persistence alone or with the interaction between wind persistence and wind speed, whereas for only two taxa was correlated solely with wind speed. These findings highlight the importance of wind persistence in pollen transport, particularly in regions where weak winds prevail for a substantial part of the year, such as Thessaloniki. Damialis et al. (2005) further demonstrated that both the movement and abundance of ragweed pollen were significantly correlated with wind persistence, while no statistically significant correlation was found between ragweed pollen abundance and wind speed, nor with the combined effect of wind speed and persistence (persistence × speed). As an expression of the plasticity of this weed species, which directly influences the duration of the ragweed allergy season, the occurrence of early-flowering ragweed forms has been recorded in Hungary (Magyar et al., 2022). With the emergence and spread of these early morphotypes, allergic symptoms may begin several weeks earlier, resulting in a prolonged ragweed pollen season.

Allergenic Potential of Ragweed Pollen and Public Health Risk

Ragweed flowers from August to October, with peak flowering in late summer, and its pollen is readily dispersed by wind over long distances. Pollen of ragweed can cause a range of adverse health effects in sensitized individuals, including allergic rhinitis (nasal congestion, rhinorrhea, and sneezing), allergic conjunctivitis (eye redness, tearing, and burning), exacerbation of asthma symptoms, and a reduced quality of life manifested by fatigue, sleep disturbances, and decreased work and school productivity). Allergic diseases have significant public health implications, including increased healthcare costs (medications and medical examinations), higher rates of absenteeism from work and school, and an increased burden on healthcare systems during the allergy season. Public health is defined as a body of knowledge, skills, and activities aimed at promoting health, preventing and controlling disease, and prolonging and improving quality of life through organized societal measures. The public health system encompasses the structures and processes that create conditions for the preservation and improvement of population health through the activities of public health stakeholders. These stakeholders include, among others, local government units, public media, companies, public enterprises, entrepreneurs, and citizens. Given the fact that ragweed pollen poses a serious health risk, which is increased by ongoing climate change, regular and systematic monitoring of ragweed occurrence and control is essential. Prevention and management measures at the community level include systematic removal of ragweed before flowering (e.g., pulling and mowing), maintenance of neglected areas (such as construction sites, roads, and agricultural land), public education and engagement of local communities in preventing the spread and ensuring timely control of ragweed, and the development of legislation that obliges landowners to implement control measures. Agnew et al. (2018) argue that it is necessary to improve our understanding of predisposing factors for ragweed allergic sensitization and disease, with a particular focus on factors that are potentially modifiable (i.e., environmental factors). Sensitization to ragweed pollen was strongly associated at levels above 5,000 pollen grains m^{-3} per year and above these levels the risk of sensitization was 12-16 times higher than in areas with low pollen levels of around 400 pollen grains m^{-3} per year. Genetic factors were strongly associated with sensitization, but almost all potentially modifiable factors were insignificant. The allergenicity of ragweed pollen is determined by the strength of its antigenic potential. Strong ragweed pollen allergens are those capable of inducing the production of large amounts of antibodies upon entry into the human body. The antigenic potency of ragweed pollen allergens depends on several properties that are necessary, though not sufficient on their own. Antigenic potency generally increases with increasing molecular weight. In addition, the allergenic potential of ragweed pollen, as well as that of other allergens, depends on the chemical structure of their molecules. Structurally, ragweed pollen allergens are predominantly proteins or proteins associated with polysaccharides or lipids. The allergenic potency of ragweed pollen is specific to each individual allergen. The specificity of individual ragweed pollen allergens depends on the content and relative proportions of aromatic amino acids, carboxyl groups, and amino groups. Each ragweed pollen allergen induces the production of specific antibodies; however, this specificity has certain limitations, such that closely related allergens may elicit cross-reactive responses. The determinants of allergen specificity are not yet fully understood. It is clear, however, that allergen specificity does not depend on the entire molecular structure of the allergen. Therefore, the molecular weight of the determinant group responsible for allergen specificity must be considerably lower than that

of the antibody. The determinant group does not necessarily have to be a protein, but may also be a polysaccharide, as is the case for certain plant pollen allergens (Bagarozzi and Travis, 1998).

Effects of Climate Change on Ragweed Pollen Production

Climate change is reflected in increasing air temperatures and rising atmospheric CO₂ concentrations. The increase in atmospheric CO₂ concentration is one of the most certain predictions of climate change models. Atmospheric CO₂ levels have increased by approximately 29% since the pre-industrial era and are expected to double again between 2050 and 2100. Ziska and Caulfield (2000) investigated ragweed pollen production under different atmospheric CO₂ concentrations, ranging from pre-industrial levels (280 $\mu\text{mol mol}^{-1}$), through current concentrations (370 $\mu\text{mol mol}^{-1}$), to projected concentrations for the 21st century (600 $\mu\text{mol mol}^{-1}$). They found that exposure to elevated CO₂ increased ragweed pollen production by 131 and 320%, respectively, compared with plants grown under pre-industrial CO₂ concentrations. The stimulation of pollen production was attributed to an increase in the number of male flowers and enhanced pollen output. From pre-industrial to current CO₂ concentrations, the number of male flowers did not change, but pollen production per inflorescence increased significantly. With further increases in CO₂ concentration, from the current 370 $\mu\text{mol mol}^{-1}$ to the projected 600 $\mu\text{mol mol}^{-1}$, no change in pollen production per inflorescence was observed; however, the number of inflorescences increased significantly, nearly doubling (Ziska and Caulfield, 2000). Wayne et al. (2002) examined ragweed pollen production by growing plants in a greenhouse under near-ambient CO₂ concentrations (350 $\mu\text{mol mol}^{-1}$) and at doubled concentrations (700 $\mu\text{mol mol}^{-1}$). They found that pollen production under elevated CO₂ conditions was 61% higher than under ambient concentrations, while increased CO₂ did not significantly affect the average pollen grain size. Elevated CO₂ also stimulated shoot biomass growth by 63%. In addition, shoot height and total seed mass were higher under elevated CO₂ conditions, by 9 and 31%, respectively. Wayne et al. (2002) concluded that a doubling of atmospheric CO₂ concentration significantly stimulates ragweed pollen production, suggesting that the incidence of hay fever and related respiratory diseases may increase in the future. Atmospheric carbon dioxide concentrations in urban environments were approximately 30% higher than those in rural areas. Under urban conditions, ragweed exhibited faster growth, earlier flowering, and produced significantly greater aboveground biomass and higher amounts of pollen. Scientific studies suggest that, as a result of projected future climate warming and increasing atmospheric CO₂ concentrations, total ragweed pollen production is likely to increase (Ziska et al., 2003). As a confirmation of this prediction, we can cite research of Hamaoui-Laguel et al. (2015) who predicted that by 2050 airborne ragweed pollen concentrations will be about 4 times higher than they are now, which mostly depends on the seed dispersal rate assumptions. About a third of the airborne pollen increase is due to on-going seed dispersal, irrespective of climate change. The remaining two-thirds are related to climate and land-use changes that will extend ragweed habitat suitability in northern and eastern Europe and increase pollen production in established ragweed areas owing to increasing CO₂. Therefore, climate change and ragweed seed dispersal in current and future suitable areas will increase airborne pollen concentrations, which may consequently heighten the incidence and prevalence of ragweed allergy.

Rasmussen et al. (2017) used the MAXENT v3.3.3k software to model the spatial distribution of all three ragweed species (*Ambrosia artemisiifolia*, *Ambrosia psilostachya*, and *Ambrosia trifida*) in Europe. MaxNet is a package in the R program that uses maximum entropy modeling to enable users to model the spatial distribution of species. The authors assessed future areas with a high risk of allergies (“high allergy risk”, HAR) under two scenarios: RCP 6.0 and RCP 8.5. RCP stands for Representative Concentration Pathway, referring to trajectories of greenhouse gas concentrations in the atmosphere. These are standardized scenarios used by the Intergovernmental Panel on Climate Change (IPCC) to project future climate change based on different levels of greenhouse gas emissions. RCP6.0 represents a scenario in which greenhouse gas emissions increase until around 2080, after which they stabilize and slow down during the second half or toward the end of the 21st century. RCP8.5 is a high-end scenario (or “worst-case scenario”) in which greenhouse gas emissions continue to rise throughout the entire 21st century without significant mitigation. In both cases, the scenarios lead to ice melt, rising temperatures, changes in precipitation, and other climatic variables, with RCP8.5 being considerably more extreme than RCP6.0. Rasmussen et al. (2017) estimate that by 2100 the distribution range of ragweed will expand toward northern and eastern Europe under all climate scenarios (Figure 1).

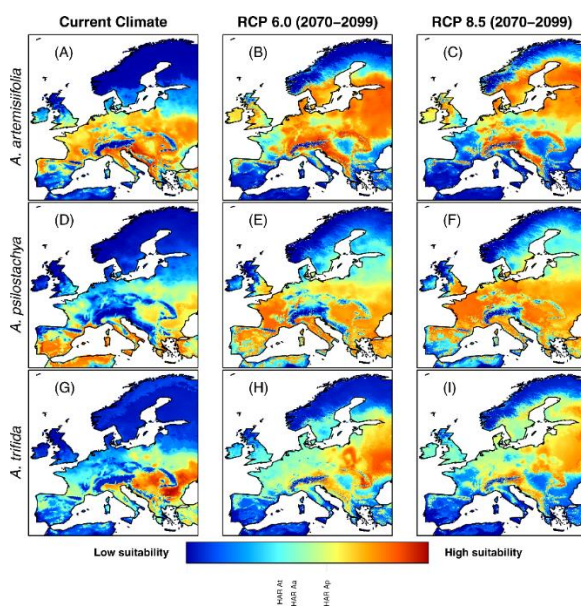


Figure 1. Habitat suitability of common ragweed (*A. artemisiifolia*) (A-C), perennial ragweed (*A. psilostachya*) (D-F) and giant ragweed (*A. trifida*) (G-I) in Europe under current climate conditions, and future climates (projections for years 2070–2099) assuming RCP 6.0 and RCP 8.5. (Rasmussen et al., 2017, doi.10.7717/peerj.3104)

New areas with a high allergy risk (“high allergy risk”, HAR) will be mainly located in Denmark, France, Germany, Russia, and the Baltic countries, overlapping with densely populated cities such as Paris and Saint Petersburg. Also, they conclude that areas in Europe affected by severe ragweed-related allergy problems are likely to increase substantially by 2100, impacting millions of people. To prevent this outcome, management strategies must be developed to limit the spread of ragweed and the establishment of new populations. Precautionary measures should restrict the dispersal of ragweed seeds and reduce existing

populations. Only through the implementation of coordinated management plans across different countries can land managers mitigate future health risks and the economic consequences of ragweed spread in Europe.

Ragweed Control as a Key Measure for Reducing Public Health Risk

In order to mitigate ragweed-induced allergic reactions, besides allergen avoidance, pharmacotherapy, and allergen immunotherapy, ragweed control measures are essential for the long-term prevention of ragweed allergies (Cheng et al., 2025). To achieve this, exceptional attention must be devoted to the control and prevention of the spread of this allergenic plant, with all measures and activities being systematic and science-based (Janjić et al., 2007). A range of measures and practices are available for the control and prevention of ragweed spread; however, all of them must be aligned with the biology of the species and applied across the entire infested area. When ragweed occurs over large areas, agrotechnical and mechanical measures are less suitable, as effective control over extensive areas within a short time period is difficult to achieve. For these and other reasons, the application of herbicides is commonly practiced for ragweed control (Janjić et al., 2007). Preventive measures are of greater importance in areas where ragweed is still absent or occurs at low densities. These measures include organizational, administrative, and educational actions aimed at the timely detection of the first ragweed individuals in a given area, followed by their removal and destruction before flowering and seed set. The most effective strategy in combating this weed is the prevention of invasion, which encompasses preventive actions such as early detection and eradication, prevention of seed dispersal, proper land management, and control of ragweed on ruderal habitats (Janjić 1999, Janjić et al., 2011).

Since ragweed spreads only by seed, therefore, the strategic basis for controlling this weed is the prevention of viable seed production. In areas where ragweed has not yet been recorded or where only isolated plants are present, early detection is crucial, followed by the timely uprooting of plants and prevention of seed set and further spread. In regions where ragweed is already widespread and well established, control strategies are likewise based on preventing seed production (Bohren, 2008), although the organization of control measures is considerably more complex. Besides herbicides, ragweed control can be achieved through non-herbicidal measures as a proper maintenance of grasslands and stubble, measures (pulling, mowing, mulching, soil tillage), biological and physical measures. Grassland management should ensure that perennial species resume growth in spring at optimal densities, allowing them to effectively compete with ragweed (Buttenschön et al., 2010, cited in Mitrić et al., 2015).

Mechanical control should be carried out in a way that completely destroys the whole plant, without the possibility of regeneration. Such efficiency is achieved only by uprooting, while mowed ragweed will regenerate to a certain extent. Selected herbicides, applied at a certain dose and phenophase of ragweed, must ensure complete plant death, therefore the effectiveness of the applied herbicides must be monitored to the end. Any measure that does not ensure complete plant death must be supplemented with other measures that will enable a complete interruption of the life cycle (Bohren, 2008, cited in Mitrić et al., 2015). The ragweed stem is easily broken, but ragweed has a pronounced ability to regenerate. It tolerates damage caused by removing the top of the stem from the foliage and has a high

regeneration capacity, which allows the plant to re-flower, produce pollen and produce seeds after mowing or other disturbances in growth. The ability of regeneration depends on the phenophase of the ragweed in which it was mechanically cut-mown, i.e. in which it was treated with herbicides, as well as on the dose of herbicide. Thus, Nedelcu et al. (2010) indicate that the regeneration ability was greater if ragweed was controlled when it had 8-10 leaves, in relation to when it had 5-6 leaves, or 3-4 leaves. Also, the regeneration ability did not depend only on the plant phenophase, but also on the applied herbicides. The same authors state that when were applied the active substance foramsulfuron+iodosulfuron-methyl-sodium in the phenophase 8-10 leaves, the degree of regeneration was 54%; with the active substance tembotrione, at the same phenophase, 34%, and when were applied the active substance terbuthylazine + bromoxynil heptonoate, there was no regeneration. With increasing herbicide doses, the regeneration ability of ragweed decreased and was the lowest when it was used recommended dose of herbicides. Mataruga (2006) determined that the efficiency of paraquat decreases at second estimate because of ragweed regeneration. Uprooting should be done before flowering, and it can be done in smaller areas, with low and medium ragweed abundance. Uprooted ragweed plants must be kept out of contact with the soil after uprooting, and it would be best to place them into plastic bags, then dry or compost them (Buttenschön et al., 2010, cited in Mitrić et al., 2015).

Biological measures of ragweed control are becoming more important. In many countries, a large number of authors have studied the possibility of biological control of ragweed. Some types of pathogenic organisms and harmful insect species can be used to control ragweed. For example, the fungus *Fusarium oxysporum* f. sp. *erythroxyli* (its phytotoxic protein designated as NEP 1) and *Pseudomonas syringae* pv *tagetis* can cause necrosis and desiccation of ragweed leaves (by 60-80%). *Fusarium* can reduce the dry mass of the above-ground part of ragweed by 41%, and *Pseudomonas* by as much as 82%. Bohar and Kiss (1999) established the presence of *Sclerotinia sclerotiorum* as a pathogen of ragweed, and Bohar and Schwarezinger (1999) *Septoria* spp. in America, one species has even been identified, which was called *Septoria ambrosiae*. *Plasmopara halstedii* and *Puccinia xanthii* cause infection in ragweed, but due to their low aggressiveness, ragweed plants continue to grow (Arsenijević et al., 1996; Petrović, 1997; Vajna, 2002; Petanović et al., 2000, cited in Mitrić et al., 2015).

In the biological control of ragweed, the use of various insect species is also possible. Igrc (1987) determined that 28 species of insects have been identified that use ragweed for their food, however, due to their polyphagous nature, they cannot be successfully used to control it. Research of *Ophraella communa* and *Epiblema strenuana* shows that they have strong potential in biological control of ragweed (Zhou et al., 2014; Kim and Lee, 2019). They exert effective control over the proliferation and dissemination of ragweed through direct herbivory on its leaves and stems, thereby diminishing its reproductive potential and constraining its growth and spread. The *Zygogramma suturalis* (F.) and *Epiblema strenuama* (Walker) are most effective in controlling ragweed (Igrc, 1987, 1988). In conditions with low predator pressure, these insects can cause major damage, but they cannot reduce the number of ragweed plants. Other insect species such as *Stobaera concinna* (Stal), *Trigonorhinus tomentosus* (Say), *Euaresta bella* (Loew), *Tarachidia condefacta* (Hübner) have been studied in some countries (Russia, Australia, Yugoslavia, China) for ragweed control (Reznik et al., 1994; Sheppard et al., 2006).

Thermal weed control is an alternative to chemical or mechanical control and is suitable for those areas where mechanical control is not possible or chemically not allowed. Thermal control would be particularly suitable for non-agricultural areas, especially areas around roads, where the use of herbicides is limited. The principle of thermal control is based on the fact that temperatures above 60°C in plants cause protein denaturation. This leads to irreversible damage to plant tissues and plant necrosis. Thermal weed control machines use an open flame, heated vapor and hot water or steam. Thermal control would be suitable in organic agriculture, however, most thermal weed control machines are more adapted for smaller areas, such as the edge of the sidewalk, but they are not suitable for agricultural areas and the area around roads (shoulders).

Sölter and Verchwele (2014) in a comparative study of the effectiveness of thermal control of ragweed, herbicide treatment (dicamba and MCPA) and mowing determined that herbicides are significantly more effective than thermal treatment and mowing. The authors used open flame at 600°C, superheated air at 370°C and hot water at 99°C for thermal control of ragweed. Also, they treated ragweed twice, when it had 6-8 leaves (BBCH 16-18) and when it was already branched and had 2-9 shoots (BBCH 22-29). Significantly greater reduction in weed mass was observed in younger stages of ragweed. Thermal control of agricultural land is carried out using specially designed devices, the so-called flame cultivators ("weed burners") that use various fuels to produce a flame, which directly destroys plants.

CONCLUSION

Climate change, reflected in rising air temperatures, increased atmospheric CO₂ concentrations, and a prolonged growing season, will enhance habitat suitability for ragweed, enabling its spread into new areas and strengthening its invasive potential. Under elevated CO₂ conditions, ragweed produces a higher number of male flowers, and the pollen is often more allergenic because it contains a greater amount of allergens per grain. Under altered climatic conditions, ragweed begins flowering earlier and ceases flowering later, resulting in prolonged exposure to pollen throughout the year. Therefore, systematic removal of ragweed before flowering is essential, along with the maintenance of neglected areas (construction sites, roadsides, agricultural fields), as well as public education and the education of local authorities, and the legal obligation of landowners to carry out mandatory ragweed control measures.

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SELECTIVITY AND EFFICACY OF FLUROCHLORIDONE WITH OTHER HERBICIDES IN WEED CONTROL IN PROCESSING TOMATO (*Solanum lycopersicum* L.)

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Abstract: For weed control in processing tomato new herbicides need to be registered. Flurochloridone with metobromuron/dimethenamid-P was applied before and after transplanting to assess its efficacy and crop injury. All treatments provided good (75-90%) to excellent (>90%) efficacy in weed control. Also, all four treatments caused crop injury, whereby treatment with metobromuron caused higher damage. Further research must be conducted with different herbicides and rates, to keep excellent efficacy but reduce crop injury.

Keywords: Processing tomato, Flurochloridone, Weed control, Efficacy, Crop injury

INTRODUCTION

Over the last fifteen years, modern agriculture has changed in many ways. Climate changes, increased world population and less arable land available, are three factors which are pushing modern agriculture forward. Due to these three factors, the global need for food has increased, so yield per growing area must be increased. On the other hand, one of the main problems in vegetable growth, including processing tomato (*Solanum lycopersicum* L.), is that at the same period of time the European Union has withdrawn many herbicides, with emphasis on some very important for vegetable production, so weed control in this crop has become troublesome (EFSA, 2025). Climate changes are also one of the key factors in combination with increased transport worldwide, which are visible due to the shift in weed population across fields. Four out of the last five years were with less precipitation or no precipitation during July and August, and with increased average temperature compared with the multi-year average (RHMZ, 2025). If compared to the period of fifteen to twenty years ago, new weeds are becoming more dominant compared to others, which implies that new practices in weed management need to be developed. Although, C₄ and CAM plants are becoming more dominant if compared to C₃ plants, due to their better adaptation mechanism to drought and high temperatures (Božić, 2018). Some of the most dominant weed species in late spring grown vegetables in Serbia, which are becoming a modern threat worldwide as well, are *Abutilon theophrasti* Medik, *Amaranthus* spp., *Chenopodium* spp., *Datura stramonium* L, *Echinochloa crus-galli* L. P.Beauv, *Setaria* spp., *Solanum nigrum* L., *Sorghum halepense* (L) Pers., *Portulaca oleracea* L., *Orobanch*

spp. and *Cuscuta* spp. (Konstantinović et al., 2020; Živković et al., 2024). Their dominance compared to other weed species because of the adoption mechanism, in combination with herbicide downdraw and resistance development are serious problems with which farmers all over the world are facing. Therefore, the goal of this study was to find new solutions for weed management in processing tomato, and to evaluate its efficacy and crop safety.

MATERIAL AND METHODS

Experimental site. The field experiment was conducted at the experimental field of the Institute of Vegetable crops Smederevska Palanka in Smederevska Palanka, during 2025 growing season. The experiment was arranged as a split-plot design with two herbicide combinations as main plots and two timing of application as subplots as well as weedy treatment - control (Table 1).

Table 1. Treatments applied in the study

Treatment	Time of application	Herbicide 1	Rate (g a.i. ha ⁻¹)	Herbicide 2	Rate (g a.i. ha ⁻¹)
Control	PRE-EM	/		/	
	POST-EM	/		/	
1	PRE-EM	metobromuron	1000	flurochloridone	500
	POST-EM	metobromuron	1000	flurochloridone	500
2	PRE-EM	dimethenamid-P	864	flurochloridone	500
	POST-EM	dimethenamid-P	864	flurochloridone	500

Both weedy subplots were transplanted at the same time with treated plots. Applied herbicide treatments included flurochloridone (Racer[®] - ADAMA Agricultural Solutions Ltd., Golan Street Airport City, Israel) a phytoene desaturase inhibitor (PDS - HRAC 12) applied at 500 g a.i. ha⁻¹ in tank-mix combination with metobromuron (Proman[®] - Certis Belchim, Londerzeel, Belgium), an inhibitor of photosynthesis at photosystem two (PSII inhibitor - HRAC 5) applied with 1000 g a.i. ha⁻¹ and dimethenamid-P (Frontier super[®]- BASF SE, Ludwigshafen RP, Germany) an inhibitor of very-long chain fatty acid synthesis (VLCFA - HRAC 15) applied at 864 g a.i. ha⁻¹ as main plots. Herbicides were applied before transplanting PRE-EM and after transplanting POST-EM. Main plots were 2,5 x 2 meter and contained 4 rows of tomato seedling transplanted on 0.5 x 0.25 meters distance with 10 plants in each row, so 40 plants contained in each plot. First transplanting was conducted on June 20th after which immediately herbicide application was conducted in the other subplots. Second transplanting was conducted on June 25th (5 days after PRE-EM herbicide application) whereby immediately after transplanting POST-EM herbicide application was conducted. Seedlings were transplanted when three true leaves were developed (BBCH 13). After 2 hours of each transplanting/herbicide application, the field was irrigated with an irrigation sprinkler nozzle which delivers 10 L of water per square meter per hour. The field was irrigated intensively in the first ten days after transplanting (DAT) so tomato seedlings could survive extremely high temperatures during this period of year (Table 2).

Table 2. Weather data and irrigation intervals for the period of 10 days after first transplanting

transpiration															
	June										July				
Date	20	21	22	23	24	25	26	27	28	29	30	1	2	3	4
Irrigation (h)	3	/	/	3.5	/	/	/	4	/	/	3.5	/	3.5	/	4
Maximum air temperature (°C)	28.3	27.6	29.8	33.9	33.4	37.4	38.8	30.6	29.1	32.0	35.4	32.9	33.3	36.9	38.2
Minimum air temperature (°C)	10.6	8.6	10.1	12.0	15.5	17.2	19.3	18.8	15.4	18.6	17.5	11.8	11.4	12.7	21.5
Precipitation (mm m ⁻²)	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0

The seedlings were grown in a 104 openings styrofoam container, whereby the seeds were sown late on May 8th. Herbicide application was conducted with a battery powered backpack sprayer “Farm® KF-16C-47” which delivers a constant pressure. A four-nozzle boom with Lechler IDK12002 nozzles was used. The pressure was 276 kPa whereby the speed was 4.56 km h⁻¹ (Table 3).

Table 3. Spraying parameters in research

Pressure (kPa)	Speed (km h ⁻¹)	Flow rate (L min ⁻¹)	Spray volume (L ha ⁻¹)	Nozzle specifications
276 ±10%	4.56	0.75	200	Lechler IDK 12002

Before herbicide application, a soil analysis was conducted (Table 4). Since the soil belongs to a heavy clay loam texture and contains 49.3% of clay, higher rates for tank-mixture of each herbicide must be applied, to achieve good soil activity but also not too high because of crop injury.

Table 4. Soil analysis results (0-30cm)

pH (H ₂ O)	pH (KCl)	CaCO ₃ (%)	Organic matter (%)	Total N (%)	P ₂ O ₅ (mg 100g ⁻¹)	K ₂ O (mg 100g ⁻¹)	Sand	Fine sand	Silt	Clay
6.31	5.91	0.34	2.25	0.15	38.28	39.27	5.1	21.1	24.5	49.3

After 28 days of each herbicide application, crop and weed parameters were taken for selectivity and efficacy. Tomato plant number per meter, tomato height and biomass were taken, as well as weed spectrum, density and biomass. After sampling, plant material was dried in air oven at 75°C until constant weight. The data has been analyzed by ANOVA, LSD and Tukey test, with IBM SPSS Statistics, Version 26.0 and were presented as table and graphs.

RESULTS AND DISCUSSION

Weed density and weed composition. Present weeds in the study were *Abutilon theophrasti* Medik., *Amaranthus* spp., *Datura stramonium* L., *Echinochloa crus-galli* L. P. Beauv and *Portulaca oleracea* L (Table 5). Due to the high content of clay in the soil profile (49.3%), and the increased amount of irrigated water necessary after transplanting/herbicide application, the two most dominant weed species in this study were *Echinochloa crus-galli*

a hygrophilous weed (F₄) which prefers to grow in fields with no water deficiency, even flooded (Jovanović and Rančić, 2025). *Portulaca oleracea* was the second most dominant weed species in this study, due to its high-water requirements and possibility to change from C₄ metabolism to CAM (Ren et al., 2011). A difficult to control weed in processing tomato with an optimum germination temperature range from 20-30°C such as *Datura stramonium* was also present (Jursik et al., 2004), as well as *Abutilon teophrasti* and *Amaranthus* spp., a nitrophilous weed (Radicetti et al., 2016; Vrbničanin et al., 2004), but with a less dense population. Weed composition and weed densities are given in Table 5.

Table 5. Average weed density per treatment (plants m⁻²) 28 DAT (Tukey, $\alpha=0.05$)

Treatments	Subplot	Weed species				
		<i>Abutilon teophrasti</i>	<i>Amaranthus</i> spp.	<i>Datura stramonium</i>	<i>Echinochloa crus-galli</i>	<i>Portulaca oleracea</i>
Control	PRE-EM	7.33 b	4.00 b	9.67 b	41.67 b	36.33 b
	POST-EM	7.50 b	5.00 b	9.00 b	40.33 b	34.67 b
metobromuron + flurochloridon	PRE-EM	0.00 a	0.00 a	3.67 a	5.00 a	0.83 a
	POST-EM	0.00 a	0.00 a	1.00 a	7.00 a	0.17 a
dimethenamid-P + flurochloridon	PRE-EM	1.33 a	0.00 a	0.33 a	2.67 a	0.00 a
	POST-EM	3.00 a	0.00 a	0.33 a	4.00 a	0.00 a

All four sublots showed statistically very significant differences in weed density compared to equivalent control treatments. Statistically no significant differences were observed between two treatments and between subplots in weed density of all five present weed species. Treatment 2. (dimethenamid-P + flurochloridon) provided less weed density in control of all weed species except *Abutilon teophrasti*. Compared to untreated control plots, both treatments applied either as PRE-EM or POST-EM provided 100% of control on *Amaranthus* spp. The percent of dry biomass reduction is given in Table 6.

Table 6. Average dry biomass reduction (%) 28 DAT (Tukey, $\alpha=0.05$)

Treatments	Subplots	Weed species				
		<i>Abutilon teophrasti</i>	<i>Amaranthus</i> spp.	<i>Datura stramonium</i>	<i>Echinochloa crus-galli</i>	<i>Portulaca oleracea</i>
Control	PRE-EM	0.00 a	0.00 a	0.00 a	0.00 a	0.00 a
	POST-EM	0.00 a	0.00 a	0.00 a	0.00 a	0.00 a
metobromuron + flurochloridon	PRE-EM	100.00 b	100.00 b	63.89 b	72.90 b	88.08 b
	POST-EM	100.00 b	100.00 b	79.37 b	51.08 b	91.61 b
dimethenamid-P + flurochloridon	PRE-EM	95.80 b	100.00 b	92.06 b	81.50 b	100.00 b
	POST-EM	88.11 b	100.00 b	86.67 b	70.76 b	100.00 b

The percentage of dry biomass reduction of *Amaranthus* spp. was 100% in all four subplots, whereby 100% of dry biomass reduction for *Abutilon teophrasti* was observed in both sublots of treatment 1. (metobromuron + flurochloridon) and for *Portulaca oleracea* 100% of dry biomass reduction was observed in treatment 2. (dimethenamid-P + flurochloridon) (Table 6). Both treatments were least efficient in *Echinochloa crus-galli* control, where the percent of dry biomass reduction varied from 51.08 but was not higher than 81.50%. The percent of dry biomass reduction of *Datura stramonium*, a difficult to control weed species in processing tomato was higher in both subplots of treatment 2. (dimethenamid-P + flurochloridon) with excellent 92.06% and satisfactory 86.67% in before and after transplanting subplots, respectively.

Another parameter followed in this study was crop injury. Crop injury was assessed by counting survived tomato plants in one meter of row length and by sampling plants and calculating the percentage of dry biomass reduction. Both treatments applied both ways caused dry biomass reduction in a serious percent (Table 7).

Table 7. Average crop injury parameters measured in the study 28 DAT (Tukey, $\alpha=0.05$)

Treatments	Subplots	Number of plants per meter	Dry biomass reduction (%)
Control	PRE-EM	4.00 b	0.00 a
	POST-EM	4.00 b	0.00 a
metobromuron + flurochloridon	PRE-EM	2.70 a	81.23 c
	POST-EM	2.30 a	77.41 c
dimethenamid-P + flurochloridon	PRE-EM	4.00 b	75.60 b
	POST-EM	4.00 b	52.43 b

Treatment 1. (metobromuron + flurochloridon) caused higher percentage of dry biomass reduction applied both ways, but more important is that this treatment caused 100% percent damage on tomato plants and reduced the average number of tomato plants per meter, which has a direct impact on the stand count and final yield (Table 7).

CONCLUSION

According to the present one-year data, both herbicide treatments applied either before or after tomato transplanting, caused very high crop injuries. Some of those treatments caused 100% injury and must be considered as phytotoxic. The efficacy of all four subplots varied, but statistically no significant differences were observed except for *Echinochloa crus-galli* dry biomass reduction. Both treatments did not provide excellent control of *Echinochloa crus-galli* and *Datura stramonium* compared to all three other weed species. Stronger crop injuries in treatment 1. (metobromuron + flurochloridon) compared to treatment 2. (dimethenamid-P + flurochloridon) might be a result of adding metobromuron which acts synergistic with flurochloridon as well as due to the foliar activity of metobromuron as a PSII inhibitor compared to dimethenamid-P with only soil activity (Idziak and Woznica, 2020). According to the literature based on previous similar studies in processing tomato across the world, this study will be continued with other herbicide combinations, lower herbicide rates and different timing of application to provide hopefully new results with less crop injuries and with higher efficacy.

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QUALITY AND SAFETY OF AGRICULTURAL PRODUCTS AS A SOURCE OF COMPETITIVENESS OF FARM HOLDINGS

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Abstract: In contemporary business conditions characterized by intense market competition, agricultural farms face the need to continuously improve their market position. The quality of agricultural products is increasingly recognized as a key factor and one of the primary sources of competitive advantage in the agri-food sector. The aim of this paper is to examine the role of agricultural product quality in strengthening the competitiveness of agricultural farms in the Republic of Serbia. The research is based on the assumption that a higher level of product quality enables better market access, greater consumer trust, more stable business performance, and long-term farm growth. The research results indicate a strong and statistically significant relationship between the quality of agricultural products and farm competitiveness, while also confirming the security role of product quality, as it directly contributes to food safety, the stability of contemporary agrarian systems, and the protection of public health. In this paper, the concept of safety refers exclusively to food safety, understood as the ability of agricultural products to meet health, hygiene, and regulatory requirements and to protect consumer health. The conclusions of the paper may serve as a basis for developing business strategies for agricultural producers, as well as for improving agricultural policies aimed at enhancing product quality and the market sustainability of agricultural farms.

Keywords: Product quality, Competitiveness, Agricultural farms, Market, Agriculture, Food safety

INTRODUCTION

Modern agriculture faces numerous challenges arising from market globalization, rapid technological change, climate-related risks, and shifting consumer preferences. Agricultural farms no longer operate within closed and locally limited systems but are increasingly becoming part of a broader market environment in which competitiveness is based on the ability to ensure consistent quality, product safety, and compliance with market and regulatory requirements (FAO, 2020; OECD, 2021). In contemporary agrarian systems, the quality of agricultural products is increasingly considered within security frameworks in order to ensure food safety, public health protection, and the overall stability of consumer and agrarian communities. Under such conditions, traditional models of competition based solely on price are losing importance, while the focus is increasingly shifting toward non-price factors of competitiveness. Among these, product quality occupies a central position, as it enables differentiation of supply, strengthens consumer trust, and facilitates access to more demanding markets. Vujčić et al. (2011) emphasize

that a product represents the way in which each enterprise aligns its capabilities and available resources with customer needs and requirements in order to satisfy them. One of the key objectives of every enterprise is the reliable and cost-effective delivery of the final product to the end user (customer). Within this supply chain, preserving product quality is crucial, as well as retaining existing customers and attracting new ones through recommendations (Nedeljkovic et al., 2023). Quality in agriculture does not refer solely to the physico-chemical characteristics of products, but also encompasses production methods, food safety, traceability, the application of standards, and adherence to the principles of sustainable development. Contemporary competitiveness theory indicates that quality represents a strategic resource capable of ensuring long-term competitive advantage, particularly in sectors characterized by pronounced market and production risks, such as agriculture (Porter, 1985). Daily changes in economic market conditions have imposed the need for a serious approach to planning and organizing all business segments in agriculture and agribusiness, making decision-making a matter of crucial importance for every manager or business organizer (Nedeljković et al., 2017).

In both domestic and international scientific literature, the competitiveness of agricultural farms is examined through the lenses of product quality, market orientation, and institutional support for agricultural development. Research findings suggest that the quality of agricultural products represents a central source of competitive advantage, as it enables product differentiation, more stable market positioning, and the long-term sustainability of farm operations. In addition to quality, the importance of entrepreneurial capabilities of farm holders, access to financial support, and the development of market activities is emphasized, as these factors jointly contribute to strengthening the competitiveness of the agricultural sector. Particular emphasis is placed on the role of human capital and education in the development of agribusiness, as well as on the need to align production with contemporary standards and market requirements. Such an integrated approach confirms that competitiveness in agriculture is not the result of a single factor, but rather of the synergistic interaction of product quality, market strategies, and the institutional environment (Vujičić et al., 2022a; Huang, 2021; Vujicic et al., 2022b; Vujicic et al., 2024).

In the Republic of Serbia, agriculture plays a significant role in overall economic development, both through its contribution to gross domestic product and through employment and the preservation of rural areas. However, agricultural farms face a number of structural challenges, including fragmented production, limited financial resources, and insufficient market orientation. In such an environment, improving product quality represents one of the key mechanisms for strengthening competitiveness and adapting to the requirements of both domestic and international markets, particularly in the process of alignment with European Union standards. Although contemporary literature increasingly highlights the importance of quality as a factor of competitiveness, there remains a need in domestic research for empirical analyses that examine this relationship in greater detail within Serbian agricultural farms. It is especially important to assess how producers perceive product quality, which measures they apply to improve it, and what impact quality has on market position and long-term farm development.

The aim of this paper is to identify and analyze the role of agricultural product quality as a source of competitiveness for agricultural farms, as well as to examine the extent of its impact on the market and development performance of farms in the Republic of Serbia.

MATERIAL AND METHODS

In order to examine the role of agricultural product quality as a source of competitiveness of agricultural farms in the Republic of Serbia, an empirical study was conducted using a quantitative research methodology. Data was collected through a structured questionnaire during the period from June to November 2025. The study included a total of 114 respondents, owners or holders of agricultural farms located in the Republic of Serbia. A convenience sampling approach was applied, focusing on farm holders who were accessible through agricultural associations and local networks. The questionnaire was distributed in both electronic and printed formats. For the purposes of the research, a five-point Likert scale was used (1 - strongly disagree; 5 - strongly agree). The internal consistency of the multi-item scales was assessed using Cronbach's alpha coefficient. The reliability values were satisfactory for all constructions ($\alpha > 0.70$), indicating good measurement consistency.

Table 1. Scale reliability

Construct	Number of items	Cronbach's α
Product Quality (APQ)	6	0.84
Market Activities (FMA)	6	0.81
Farm Competitiveness (CAF)	6	0.86

For each variable, six statements were formulated in accordance with relevant literature and previous research in the field of quality and competitiveness.

The theoretical research model consisted of the following variables:

- **Independent Variable A - Agricultural Product Quality (APQ):** product safety (food safety), quality standards, consistency, certifications, consumer perception. In this study, product safety is treated as an integral component of product quality and not as a separate variable.
- **Independent Variable B - Farm Market Activities (FMA):** branding, promotion, distribution, market presence.
- **Dependent Variable C - Competitiveness of Agricultural Farms (CAF):** market position, sales, income stability, farm growth.

The model is based on the assumption that product quality, both independently and in combination with market activities, has a significant impact on the competitiveness of agricultural farms.

The objectives of the research were to:

- determine whether agricultural product quality affects farm competitiveness.
- examine the impact of market activities on competitiveness.
- analyze the joint effect of product quality and market activities on competitiveness.

The research hypotheses were formulated as follows:

- **H01:** Agricultural product quality does not affect farm competitiveness.
- **Ha1:** Agricultural product quality affects farm competitiveness.
- **H02:** Market activities do not affect farm competitiveness.
- **Ha2:** Market activities affect farm competitiveness.
- **H0:** Product quality and market activities do not affect farm competitiveness.
- **Ha:** Product quality and market activities affect farm competitiveness.

EMPIRICAL RESEARCH: AGRICULTURAL PRODUCT QUALITY AS A SOURCE OF FARM COMPETITIVENESS

The research was conducted on a sample of 114 respondents' holders or owners of agricultural farms in the Republic of Serbia. Data was collected through a structured questionnaire during 2025. The questionnaire included statements measured using a five-point Likert scale.

Table 2. Structure of respondents by gender

Gender of respondents	Number of respondents	%
Men	72	63.2
Women	42	36.8
Total	114	100

Table 3. Structure of respondents by age

Age category	Number of respondents	%
Up to 35 years	38	33.3
36-55 years	54	47.4
Over 55 years	22	19.3
Total	114	100

Table 4. Structure of respondents by education

Level of education	Number of respondents	%
Secondary education	66	57.9
Higher/university education	48	42.1
Total	114	100

Table 2 presents the basic demographic characteristics of the respondents included in the study. The sample consists of 114 respondents, with men representing the majority, which is consistent with the structure of agricultural farm holders in Serbia. The largest proportion of respondents belongs to the age group of 36-55 years, indicating that the sample comprises an economically active population with substantial experience in agricultural production. Most respondents have secondary education, while a significant proportion have higher or university-level education, which contributes to the reliability of the obtained responses.

Table 5. Pearson correlation of variables

Variables	APQ	FMA	CAF
Agricultural Product Quality (APQ)	1.000	0.421	0.764
Farm Market Activities (FMA)	0.421	1.000	0.602
Competitiveness of Agricultural Farm (CAF)	0.764	0.602	1.000

Table 5 presents the results of the Pearson correlation analysis among the key variables of the study. A strong positive correlation was identified between the quality of agricultural products and farm competitiveness, indicating that a higher level of quality contributes to a better market position. Market activities also show a moderate to strong association with competitiveness, while the relationship between product quality and market activities is of moderate strength. The results confirm the interrelatedness of the analyzed variables and justify the application of further regression analysis.

Table 6. Results of the multiple regression analysis

Variable	B	Std. Error	Beta	t	p
Constant	0.512	0.214	-	2.39	0.018
Product Quality (APQ)	0.658	0.067	0.621	9.82	<0.001
Market Activities (FMA)	0.274	0.061	0.331	4.49	<0.001

Table 7. Multiple regression results (dependent variable: Farm Competitiveness- FC)

Predictor	B	Std. Error	Beta	t	p	VIF
Constant	0.512	0.214	-	2.39	0.018	-
Product Quality (APQ)	0.658	0.067	0.621	9.82	<0.001	1.28
Market Activities (FMA)	0.274	0.061	0.331	4.49	<0.001	1.28
R	0.809					
R ²	0.655					
Adjusted R ²	0.649					
F (2, 111)	105.3					
p (model)	<0.001					
Durbin-Watson	1.94					

Table 6 presents the results of the multiple regression analysis examining the impact of agricultural product quality and market activities on farm competitiveness. The results indicate that both independent variables have a statistically significant effect on competitiveness, with product quality making a stronger contribution. The positive values of the regression coefficients confirm that improvements in product quality and market performance lead to a strengthening of farms' competitive position. These findings support the research hypothesis regarding the importance of quality as a source of competitiveness. The regression model was statistically significant ($F = 105.3$, $p < 0.001$) and explained 65.5% of the variance in farm competitiveness ($R^2 = 0.655$). Product quality ($\beta = 0.621$, $p < 0.001$) had a stronger effect than market activities ($\beta = 0.331$, $p < 0.001$), while variance inflation factors confirmed the absence of multicollinearity.

RESULTS AND DISCUSSION

The results of the empirical research are presented through a combination of descriptive sample analysis, correlation analysis of key variables, and regression analysis, with the aim of determining the role of agricultural product quality as a source of competitiveness of agricultural farms. The analysis was conducted on a sample of 114 respondents, owners or holders of agricultural farms in the Republic of Serbia.

Descriptive analysis indicates that the sample consists of respondents who actively participate in agricultural production and business decision-making at the farm level. In terms of gender structure, men dominate the sample, which is consistent with official

statistical data on the structure of agricultural farm holders in Serbia. However, a significant proportion of women in the sample indicates the growing involvement of women in farm management, which further contributes to the diversity of perceptions and experiences included in the study. Analysis of the age structure shows that the largest number of respondents belongs to the 36-55 age group, representing a population with substantial experience in agricultural production that is simultaneously active and adaptable to contemporary market requirements. The presence of younger respondents indicates gradual generational renewal in agriculture, while older respondents contribute to stability and continuity of knowledge and practice. Regarding educational structure, most respondents have secondary education, while a significant proportion possess higher or university-level education. Such a structure suggests that respondents have adequate knowledge and competencies to assess issues related to product quality, market activities, and farm competitiveness, thereby increasing the reliability of the obtained results.

To examine the relationships among variables, Pearson correlation analysis was applied. The results indicate statistically significant positive relationships among all analyzed variables. The strongest correlation was identified between agricultural product quality and farm competitiveness. This finding suggests that respondents who perceive a higher level of product quality also evaluate their farms as more competitive in the market. The strong association between these two variables confirms the assumption that product quality represents one of the key factors of differentiation and market success in contemporary agriculture.

Farm market activities also show a significant positive correlation with competitiveness. Respondents who invest more in promotion, distribution, communication with customers, and market presence evaluate their farms as more stable and competitive. This finding indicates that competitiveness is not solely the result of product quality, but also of the ability of farms to adequately present and place that quality on the market. The correlation between product quality and market activities is of moderate strength, suggesting that farms producing higher-quality products more frequently apply more developed market activities. This relationship highlights the interconnection between production and market dimensions of business operations, as well as the fact that high product quality alone is not sufficient if it is not accompanied by an appropriate market approach. To examine the direct impact of agricultural product quality on farm competitiveness, a simple linear regression analysis was conducted. The results show that product quality has a strong and statistically significant effect on competitiveness. The coefficient of determination indicates that a substantial portion of the variability in farm competitiveness can be explained by changes in the level of product quality. The standardized regression coefficient shows a strong positive effect, meaning that an increase in perceived product quality leads to an increase in farm competitiveness. These results confirm the alternative hypothesis that agricultural product quality represents an important source of competitiveness. The findings are consistent with contemporary theoretical approaches emphasizing that non-price factors, such as quality, safety, and product reliability, play a crucial role in the long-term market survival and development of agricultural producers.

In addition to product quality, the impact of market activities on the competitiveness of agricultural farms was also analyzed. The regression analysis results indicate that market activities have a statistically significant but moderate effect on competitiveness. The

coefficient of determination shows that market activities explain a smaller portion of the variability in competitiveness compared to product quality but still represent an important factor. The positive value of the regression coefficient indicates that more intensive market activities contribute to better market positioning of farms. These findings suggest that the competitiveness of agricultural farms depends not only on product quality, but also on the ability of producers to recognize market needs, communicate the value of their products, and ensure continuity of market presence.

Finally, a multiple regression analysis was conducted to examine the joint impact of product quality and market activities on farm competitiveness. The results show that the combined model has strong statistical significance and that both independent variables together explain a significant portion of the variability in competitiveness. The standardized coefficients indicate that product quality has a dominant contribution in explaining competitiveness, while market activities have a complementary but statistically significant effect. This finding confirms that product quality represents the foundation of competitiveness, while market activities act as a reinforcing factor.

Based on the results obtained, it can be concluded that agricultural farms that simultaneously invest in improving product quality and developing market activities achieve a more favorable market position and higher competitiveness. This confirms the main alternative hypothesis of the study regarding the importance of agricultural product quality as a source of farm competitiveness.

The discussion of the research results is focused on interpreting the obtained empirical findings in light of contemporary theoretical approaches to competitiveness, quality management, and the development of agricultural farms. Starting from the main objective of the study examining the role of agricultural product quality as a source of farm competitiveness the research results provide a significant contribution to understanding the factors that shape the market position of agricultural producers in the Republic of Serbia. The results of the correlation analysis indicate a strong positive relationship between the quality of agricultural products and farm competitiveness. This finding confirms theoretical perspectives according to which product quality represents one of the key non-price factors of competitiveness, particularly in sectors exposed to intense market competition and increasing consumer demand. In modern agriculture, quality is no longer viewed solely through the physical characteristics of products, but also includes aspects such as food safety, standardization, traceability, and producer reputation, which further strengthens its role in farm market positioning.

The findings of this study are consistent with previous empirical research showing that agricultural farms that invest in improving product quality achieve more stable revenues, easier market access, and greater long-term business sustainability. The strong impact of product quality on competitiveness, confirmed by regression analysis, indicates that quality represents a fundamental prerequisite for successful business operations, regardless of farm size or type of production. This finding is particularly significant in the context of small and medium-sized agricultural farms, which often face resource constraints and must seek alternative sources of competitive advantage compared to price-based competitors. The results of the regression analysis further confirm that market activities have a statistically significant but weaker impact on competitiveness compared to product quality. This

suggests that market activities, such as promotion, branding, and distribution, play a supportive and reinforcing role in the core competitive foundation built through product quality. In other words, market performance can enhance product visibility and recognition, but it cannot compensate for a lack of quality in the long term.

The quality of agricultural products in contemporary agrarian systems is increasingly viewed as a security category, given that food safety represents one of the key elements of public health and, consequently, social stability. According to the World Health Organization (WHO, 2021), unsafe and substandard food represents one of the major global risks to population health, while the Food and Agriculture Organization of the United Nations (FAO, 2021; FAO et al., 2022) emphasizes that food quality and safety function as public goods, as they directly affect consumer confidence and the long-term sustainability of agricultural production. In this context, improving the quality of agricultural products represents an important mechanism for preventing health, social, and economic risks in contemporary societies.

The moderate relationship between product quality and market activities indicates that producers who offer higher-quality products are more likely to develop and implement more active market strategies. This finding can be interpreted as evidence of the growing market orientation of agricultural farms, as well as an indication that product quality motivates producers to invest more intensively in promotion and product placement. At the same time, the results point to existing potential for improving market activities among farms that produce high-quality products but do not yet fully utilize their market potential.

Multiple regression analysis confirmed that the combined effect of product quality and market activities has a strong and statistically significant impact on farm competitiveness. The dominant contribution of product quality within this model further emphasizes its central role in the formation of competitive advantage, while market activities perform a complementary function. This result indicates that sustainable competitiveness in agriculture requires an integrated approach that simultaneously improves production and market aspects of business operations. In the context of the integration of the domestic market into broader regional and international flows, product quality becomes a prerequisite for meeting the standards and requirements of contemporary markets. Farms that fail to achieve an adequate level of quality face limited market access and reduced opportunities for growth and development.

It is important to note that the results of this study refer to the examined sample and cannot be fully generalized to all agricultural farms in Serbia. Nevertheless, the findings provide relevant guidelines for further research and practical application, particularly in the areas of business strategy development and agricultural policy formulation aimed at improving quality and enhancing the competitiveness of domestic agriculture.

CONCLUSION

The aim of this research was to examine the role of agricultural product quality as a source of competitiveness of agricultural farms in the Republic of Serbia. Based on contemporary theoretical approaches to competitiveness and quality management, an empirical study was conducted on a sample of 114 respondents, providing a foundation for analyzing the

relationship between product quality, market activities, and farm competitiveness. The research results clearly indicate that the quality of agricultural products represents a key factor of competitiveness. The strong relationship identified between product quality and competitiveness confirms that producers who invest in quality achieve a stronger market position, greater business stability, and improved prospects for long-term development. Product quality proved to be the dominant variable in explaining competitiveness, thereby confirming the main research hypothesis.

In addition to product quality, market activities were identified as an important but secondary factor of competitiveness. The results suggest that market activities contribute to strengthening competitiveness primarily as a complement to product quality. This finding emphasizes that successful market performance cannot be sustainable without an adequate level of product quality, while quality without appropriate market support does not fully realize its potential.

Based on the obtained results, it can be concluded that the competitiveness of agricultural farms requires an integrated approach that includes improving product quality, applying standards, and developing market activities aligned with the needs of modern consumers. It is particularly important for agricultural farms to recognize quality not only as a technical issue, but also as a strategic category that influences all aspects of business operations.

Improving the quality of agricultural products represents not only a market imperative, but also an important security mechanism that contributes to food security and food safety, public health protection, and the long-term stability of contemporary agrarian systems.

The study has certain limitations, primarily related to sample size and geographical scope, which indicate the need for further research using larger and more diverse samples. Future studies could include additional variables, such as innovation, digitalization, institutional support, and sustainability, in order to gain a more comprehensive understanding of the factors influencing farm competitiveness.

Despite these limitations, the results of this study provide significant theoretical and practical implications. From a theoretical perspective, the research contributes to a better understanding of the role of product quality in building competitive advantage in agriculture. From a practical perspective, the findings may serve as a basis for producers' business decision-making, as well as for shaping agricultural policies aimed at improving quality and strengthening the competitiveness of domestic agriculture.

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WOMEN'S ENTREPRENEURSHIP IN AGRICULTURE AND RURAL DEVELOPMENT IN SERBIA

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Abstract: Women's entrepreneurship in agriculture represents an important, yet still insufficiently explored, segment of rural development in the Republic of Serbia. In the context of long-standing structural challenges facing rural areas such as depopulation, population ageing, and limited economic opportunities the role of women in the development of agricultural holdings and related activities has become increasingly significant. The aim of this paper is to examine the role of women entrepreneurs in agriculture and their position within the rural development process in Serbia, with particular emphasis on the forms of entrepreneurial activities, development potentials, and constraints they face. The paper is based on an analysis of relevant domestic and international literature, as well as an examination of the institutional and socio-economic framework within which women pursue their entrepreneurial initiatives. The findings may serve as a basis for further research and for the formulation of policies aimed at providing stronger support to women in rural areas.

Keywords: Women's entrepreneurship, Agriculture, Rural development, Serbia, Sustainability

INTRODUCTION

The agricultural sector in the Republic of Serbia has very high economic and social importance, as it makes a significant contribution to gross domestic product and employs a large number of people (Milanović et al., 2020). However, for many years negative trends have been present, reflected in rural depopulation, population ageing, a decline in economic activities, and limited employment opportunities. Contemporary approaches to rural development indicate that the revitalization of rural areas cannot be based solely on primary agricultural production, but instead requires the diversification of economic activities, the strengthening of local entrepreneurship, and the more active inclusion of all social groups in development processes. Entrepreneurship is increasingly recognized as one of the key mechanisms for stimulating economic growth, employment, and social cohesion in rural areas (OECD, 2019). In the literature, women's entrepreneurship is defined as a set of entrepreneurial activities initiated and managed by women, emphasizing its role in economic empowerment, poverty reduction, and the improvement of quality of life, particularly in less developed areas. Entrepreneurs Hendratmi et al. (2022), women entrepreneurs participate in all aspects of entrepreneurship, taking risks and identifying opportunities in their environment to combine resources in innovative ways that enhance the profitability of their ventures. Hendratmi et al. (2022) further reveal that an increasing

number of women engage in entrepreneurship with the aim of achieving a better work-life balance and contributing to their communities.

Special attention in contemporary research is devoted to the role of women in the rural economy. The World Bank (2012) notes that women's entrepreneurship is often linked to agriculture, food processing, the production of traditional products, rural tourism, and other activities based on local resources and knowledge. Although women represent a significant share of the agricultural workforce and play an important role in maintaining agricultural holdings and households, their contribution is often insufficiently visible and institutionally recognized. Anupama et al. (2024) point out that women farmers play a vital role in sustaining agriculture, yet their contribution is frequently undervalued. Numerous studies indicate that women in rural areas are less likely to appear as formal owners of farms or as entrepreneurs, which directly affects their access to financial resources, incentives, and markets (FAO, 2011). The FAO and the World Bank emphasize that greater inclusion of women in entrepreneurial activities in agriculture can have a significant positive impact on productivity, food security, and sustainable rural development. FAO (2011) states that reducing the gender gap in access to resources could lead to increased agricultural production and improved food security, particularly in developing and transition countries.

Vujičić and her co-authors point out that the development of women's entrepreneurship in Serbia is shaped by a combination of individual factors, such as education and entrepreneurial skills, as well as institutional factors, including the availability of financial support and public policies (Vujičić et al., 2012, 2013). The authors particularly emphasize that women's entrepreneurship has the potential to contribute to reducing unemployment and strengthening local economies, but that this potential remains largely underutilized in practice. In addition to domestic research, relevant international literature highlights that women in rural areas often face additional barriers to entrepreneurial development. Among the most frequently identified obstacles are limited access to capital, unresolved property rights issues, weaker links to markets, and insufficient institutional support (OECD, 2019; European Commission, 2021). These challenges are particularly pronounced in agriculture, where formal ownership of land and farms often represents a basic prerequisite for accessing support measures. The contemporary concept of rural development increasingly emphasizes an integrated approach that includes economic, social, and institutional dimensions of development. Therefore, women's entrepreneurship should not be viewed solely as an issue of gender equality, but rather as an important development resource that can contribute to employment, income diversification, and the long-term sustainability of rural communities. As noted by Doss et al. (2018), the economic empowerment of women in agriculture has the potential to generate positive effects not only at the level of the individual and the household, but also at the level of the local community.

LITERATURE REVIEW

Women's entrepreneurship represents a specific segment of entrepreneurial activity that is increasingly viewed in contemporary literature as an important factor of economic and social development, particularly in less developed and rural areas. Research shows that the inclusion of women in the agricultural sector can significantly improve productivity and innovation, which are essential for maintaining market competitiveness (Vujičić et al., 2025). The OECD (2019) emphasizes that entrepreneurship in rural areas plays a key role

in diversifying economic activities, reducing dependence on primary agriculture, and strengthening the resilience of local economies. Women's entrepreneurship gains additional importance because it combines economic objectives with social and developmental effects. The World Bank (2012) highlights that the inclusion of women in entrepreneurial activities contributes to economic growth, poverty reduction, and improved social inclusion. This is particularly relevant in rural areas, where employment opportunities are limited and women's entrepreneurship often represents one of the few sustainable ways of economic engagement and population retention in villages. The findings of Vujičić et al. (2025) clearly indicate that women in agriculture, despite facing numerous difficulties, possess significant potential to improve their production activities and contribute to rural development.

International literature points out that women play a significant but often insufficiently visible role in agriculture. FAO (2011) notes that women participate in almost all stages of agricultural production, from primary production to processing and distribution, yet their contribution is often not reflected in formal ownership of resources or decision-making processes. This situation limits their access to finance, technology, and markets. Doss et al. (2018) further emphasize the problem of the "invisibility" of women's work in agriculture, noting that statistical data frequently fail to capture the actual extent of women's involvement. Eurostat (2022) shows that women are significantly underrepresented among holders of agricultural holdings compared to men, even though they constitute a substantial share of the rural workforce. They are often perceived as merely "assisting" the male head of the household, which renders their contribution invisible in official statistics (Chowdhry, 1993; Agarwal, 2003). Similar trends are observed in Serbia, where women are frequently engaged as members of family farms but less often as formal owners or holders of business activities.

The contemporary concept of rural development emphasizes the need for an integrated approach that connects the economic, social, and institutional dimensions of development. Within this framework, women's entrepreneurship is recognized as one of the factors that can contribute to employment, increased household income, and the preservation of rural communities (OECD, 2019). FAO (2020) states that women in rural areas often develop entrepreneurial activities in agricultural processing, value-added food production, rural tourism, and traditional crafts. These forms of entrepreneurship strengthen local value chains and increase the competitiveness of the rural economy. Vujičić et al. (2012) emphasize that women's entrepreneurship in Serbia has the potential to reduce female unemployment and strengthen local economies, but that its development is conditioned by institutional and market factors. The authors stress the importance of tailoring support measures to the specific needs of women, particularly in rural areas. Vujičić et al. (2013) point out that women's entrepreneurship in Serbia continues to face numerous obstacles, including limited access to financial resources and insufficient support through development policies. They conclude that without a systemic approach and long-term strategies, the potential of women's entrepreneurship remains underutilized, especially in agriculture and rural areas.

Numerous studies indicate that women entrepreneurs in rural areas face specific challenges. The World Bank (2012) identifies limited access to capital, unresolved property rights, and weaker integration into business networks as key barriers to the development of women's

entrepreneurship. The European Commission (2021) further emphasizes that institutional barriers, complex administrative procedures, and inadequately tailored support programs particularly affect women in rural areas. In Serbia, these obstacles are often linked to the formal status of farm holders, which represents a prerequisite for accessing agricultural support measures. Vujičić et al. (2012) note that women entrepreneurs in Serbia often have lower initial capital and more limited access to financial institutions, which constrains the scope and growth of their business activities. Such conditions further hinder the development of women's entrepreneurship in agriculture, where investments in equipment, standards, and technologies are necessary for competitiveness.

MATERIAL AND METHODS

In order to examine the role of women's entrepreneurship as a factor of rural development in the Republic of Serbia, this study applies a methodology that combines theoretical and empirical approaches. The starting point of the research is a detailed analysis of domestic and international literature in the fields of women's entrepreneurship, rural development, and agriculture. A review of relevant theoretical approaches and empirical studies made it possible to identify key factors influencing the development of women's entrepreneurial activities in rural areas, such as access to resources, institutional support, market conditions, education, and social context. This theoretical framework served as the basis for defining the research objectives, formulating hypotheses, and designing the research instrument, thereby ensuring methodological consistency between the theoretical assumptions and the empirical part of the study.

The empirical research was conducted using a quantitative methodology through a structured questionnaire survey. The study was carried out on a sample of 78 women entrepreneurs operating in rural areas of the Republic of Serbia, including respondents engaged in agriculture, agricultural processing, rural tourism, and other activities related to the rural economy. The sample consisted of women who are formally registered as entrepreneurs or holders of agricultural holdings, as well as those who perform entrepreneurial activities within family farms. This approach enabled the inclusion of different forms of women's entrepreneurship in rural areas and provided a more realistic assessment of their contribution to local development.

The structure of the questionnaire was designed to guide respondents gradually from general to more specific questions. The first part of the questionnaire focused on the basic sociodemographic characteristics of the respondents, including age and level of education. The second part was aimed at examining the characteristics of entrepreneurial activity in a rural context. Respondents provided information on their motives for starting a business, sources of financing, access to markets, and the challenges they face in their daily operations. Particular attention was paid to questions related to institutional support, the availability of incentives, and cooperation with local institutions, as these factors are frequently highlighted in literature as crucial for the development of women's entrepreneurship in rural areas. The third part of the questionnaire addressed the respondents' perceptions of the impact of their entrepreneurial activities on rural development. This segment examined the contribution of women's entrepreneurship to employment, increased household income, diversification of economic activities, and the

preservation of local communities. In this way, women's entrepreneurship was considered not only as an individual business activity but also as a broader development factor.

All responses in the second and third parts of the questionnaire were measured using a five-point Likert scale, where a value of 1 indicated complete disagreement with a given statement, and a value of 5 indicated complete agreement. This measurement approach enabled quantitative analysis of respondents' attitudes and comparison of different aspects of women's entrepreneurship in rural areas.

After data collection, the responses were processed and analyzed using the statistical software package SPSS. Descriptive statistics were applied to examine the basic characteristics of the sample and the distribution of responses. To analyze the relationships between key variables, correlation and regression analyses were used. The reliability of the measurement scales was assessed using Cronbach's alpha coefficient.

Table 1. Scale reliability

Measurement scale	No. of items	Cronbach's alpha (α)
Motives for starting entrepreneurship	5	0.83
Barriers to business development	6	0.81
Perceived economic effects	5	0.85
Contribution to rural development	5	0.87

The results obtained provide a solid basis for further empirical analysis and may serve as a starting point for future research in this field.

RESEARCH QUESTIONS AND HYPOTHESES

The study is guided by the following research questions:

RQ1: To what extent does women's entrepreneurship contribute to income generation and economic security in rural Serbia?

RQ2: What are the main institutional and market barriers faced by women entrepreneurs in agriculture?

RQ3: How do women entrepreneurs perceive their role in rural development and community sustainability?

Based on the literature, the following hypotheses were formulated:

H1: Women's entrepreneurship has a positive effect on household income and economic security.

H2: Limited access to finance and markets significantly constrains the development of women-owned agricultural businesses.

H3: Women entrepreneurs perceive their activities as contributing to rural development and community stability.

RESULTS AND DISCUSSION

The results of the research conducted on a sample of 78 female respondents operating in agriculture and rural areas of the Republic of Serbia provide insight into their attitudes, experiences, and perceptions related to entrepreneurial activities, economic empowerment,

and contributions to rural development. An analysis of the basic demographic and socio-economic characteristics of the sample shows that the study included women of different ages, educational levels, and entrepreneurial experience. The largest number of respondents belongs to the age group between 36 and 55, indicating women who possess considerable life and work experience while still being in a phase of active economic engagement. The presence of younger respondents (up to 35 years of age) points to the gradual involvement of younger women in entrepreneurial activities in rural areas, while the inclusion of respondents over the age of 55 confirms the continuity of women’s work and entrepreneurship in agriculture, often based on family tradition. Regarding educational structure, most respondents have secondary education, while a significant number hold higher or university-level degrees. This structure suggests that women engaged in entrepreneurship in rural areas possess the knowledge and skills necessary for independent business decision-making, monitoring market demands, and adapting to changes in their environment.

Table 2. Key descriptive results (Likert 1-5)

Key dimension	Mean	SD
Motives for entrepreneurship	4.21	0.62
Barriers to business development	3.89	0.71
Perceived economic effects	4.07	0.66
Contribution to rural development	3.94	0.69

The research results indicate that the motives for initiating entrepreneurial activities among respondents are multiple and intertwined. The most frequently cited motives relate to the need for additional or more stable income, the desire for economic independence, and the opportunity to remain and work in a rural environment without migrating to urban centers. A significant number of respondents emphasize that entrepreneurship in agriculture enabled them to balance business obligations with family life, which is particularly important given the traditional gender roles that are still prevalent in rural areas of Serbia. At the same time, some respondents state that the decision to enter entrepreneurship resulted from a lack of alternative employment opportunities, indicating that women’s entrepreneurship in rural areas often has the characteristics of “necessity entrepreneurship.” However, even in such cases, the results show that women gradually develop a sense of personal responsibility, self-confidence, and pride in their own business activities.

The respondents identified numerous obstacles they face in their entrepreneurial work. The most prominent problems include limited access to financial resources, complex administrative procedures, and insufficient institutional support. A large number of respondents believe that the conditions for obtaining loans or subsidies are unfavorable for small women-owned agricultural holdings, particularly for women who do not have property registered in their own name. In addition to financial barriers, limited access to markets represents a significant challenge, especially with regard to placing products beyond the local community. Respondents often report being forced to rely on local markets, open-air markets, or direct sales, which restricts the scale of their operations and growth potential. A lack of information about modern sales channels, as well as insufficient digital literacy among some respondents, further complicates market positioning.

The research results clearly indicate that most respondents agree that entrepreneurship has contributed to increased personal economic security and independence. Women emphasize that running their own businesses allows them greater control over income, as well as increased involvement in decision-making at the household level. These findings confirm that women's entrepreneurship has a broader social significance that goes beyond purely economic effects. A significant number of respondents state that entrepreneurial activities have increased their self-confidence, willingness to take responsibility, and more active participation in the local community. Some respondents note that they have become role models for other women in their villages, indicating the potential of entrepreneurship to act as a factor of social change in rural areas.

With regard to the impact of women's entrepreneurship on rural development, the research results show that respondents recognize their contribution through the preservation of local production, the employment of family members and other women from the surrounding area, and the enhancement of local product offerings. Particular emphasis is placed on food production, agricultural processing, and the preservation of traditional knowledge and skills.

The respondents largely believe that their business activities contribute to reducing rural depopulation, as they enable women and their families to remain in rural areas. Although they are aware of the limitations they face, most view entrepreneurship as a realistic opportunity for the long-term survival of rural communities. The research results indicate that women's entrepreneurship in agriculture represents an important, yet still insufficiently utilized, potential for rural development in Serbia. The respondents demonstrate a high level of motivation and willingness to work, but they face structural barriers that limit the further growth and development of their business activities. The findings confirm that the economic empowerment of women through entrepreneurship generates multiple positive effects, both at the individual level and at the level of the local community.

The conducted research showed that the respondents' decision to engage in women's entrepreneurship is most often based on a combination of economic and social reasons, including the need for more stable income, the desire for independence, and the opportunity to remain in a rural environment. These results are consistent with findings from both domestic and international studies, which indicate that women's entrepreneurship in rural areas often takes the form of "necessity entrepreneurship," but gradually evolves into a conscious and strategic business choice. The results related to business obstacles confirm that structural problems remain strongly present. Limited access to financial resources, insufficient institutional support, and complex administrative procedures were identified as the dominant challenges. These findings are in line with studies showing that women in agriculture are more likely to lack formal ownership of assets, which directly affects their creditworthiness and access to development funds (OECD, 2020; European Commission, 2022). Such constraints further deepen gender inequalities and reduce the development potential of local communities. A particularly important aspect of the research relates to the respondents' perception of their own economic empowerment. Most women emphasize that entrepreneurship has enabled greater financial security, as well as increased participation in household decision-making.

The research results also point to the important role of women's entrepreneurship in preserving local production and traditional knowledge. Respondents often state that their business activities are based on local resources, traditional recipes, and family knowledge, which contributes to the preservation of rural identity. These findings correspond with contemporary approaches to rural development that emphasize the importance of endogenous development potentials and local initiatives (van der Ploeg et al., 2015). Another significant finding concerns the role of women's entrepreneurship in preventing rural depopulation. The respondents largely believe that running their own business enables them to remain in rural areas and secure livelihoods for their families. This perception confirms that entrepreneurship can play a preventive role in migration processes, particularly among women, who are often the first to leave rural areas in search of more secure income sources. The results support the conclusions of authors who argue that the economic empowerment of women is a key factor of sustainable rural development (Bock, 2015; FAO, 2020).

However, the research also indicates the existence of untapped potential. Although women recognize the importance of markets and innovation, a large number of respondents still rely on traditional forms of sales and local markets. Limited digital literacy and insufficient awareness of modern distribution channels represent significant barriers to further development. This finding points to the need for targeted training and support programs that would enable women easier access to markets and greater visibility of their products. Overall, the research results clearly indicate that improving the position of women entrepreneurs requires an integrated approach encompassing financial support, education, institutional networking, and the recognition and promotion of women's work in rural areas.

CONCLUSION

The research conducted for the purposes of this paper shows that women's entrepreneurship represents a significant, yet still insufficiently utilized, factor of rural development in the Republic of Serbia. The results indicate that women in rural areas increasingly engage in entrepreneurial activities as a response to limited employment opportunities, as well as a means of achieving economic independence, professional identity, and remaining within their local communities. In this way, women's entrepreneurship goes beyond the individual level and becomes an element of broader socio-economic development in rural areas. The findings confirm that women's entrepreneurial activities contribute to increasing household income, preserving local production, and strengthening the economic resilience of rural households. These results are consistent with the findings of FAO (2019, 2021), which emphasize that the economic empowerment of women in agriculture has a direct impact on productivity, food security, and the sustainability of rural communities. In addition, the OECD (2020) highlights that the inclusion of women in entrepreneurship contributes to the diversification of rural economies and the reduction of regional development disparities.

The research also points to pronounced obstacles faced by women entrepreneurs, particularly limited access to financial resources, insufficient institutional support, and restricted access to markets. These findings confirm the conclusions of the European Commission (2022), which indicate that women in rural areas continue to be in a less favorable position in terms of access to resources, information, and support networks. A

specific contribution of this research lies in its examination of the broader social role of women's entrepreneurship. The results show that entrepreneurship positively affects the respondents' self-confidence, their role in household decision-making, and their visibility within the local community. Such findings support arguments regarding the multidimensional impact of women's economic empowerment. Based on the obtained results, it can be concluded that women's entrepreneurship in agriculture has considerable development potential, but its further strengthening requires systematic support. It is necessary to improve access to finance, provide educational programs focused on market and digital empowerment of women, and develop institutional mechanisms that recognize and value women's contribution to rural development.

This study has several limitations. The sample size is relatively small and limited to women entrepreneurs who were accessible through local networks, which may restrict the generalizability of the results. In addition, the study relies on self-reported data, which may be affected by subjective perceptions and social desirability bias. Future research should include larger and more regionally diverse samples and combine survey data with objective performance indicators.

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THE ROLE OF MEDICINAL PLANT SPECIES IN THE GREEN TRANSFORMATION OF AGRICULTURE: LINKING BIODIVERSITY CONSERVATION WITH ECONOMIC VALUE

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Abstract: The cultivation of endangered medicinal plant species is a key element in the green transformation of agriculture, linking species conservation with sustainable market development. The cultivation of endangered and/or protected medicinal plant species represents an effective conservation strategy, reducing harvesting pressure on wild populations while ensuring the preservation of genetic resources. Their production systems are suitable for low-input and agroecological practices, often requiring minimal chemical inputs and enabling cultivation on marginal or less intensively farmed land. Furthermore, these medicinal plants support climate-resilient agriculture due to their adaptability to specific ecological conditions and their role in crop diversification. The development of sustainable value chains, supported by traceability, certification, and environmentally friendly processing technologies, increases their market value while contributing to Green Agenda objectives, including biodiversity protection, circular economy principles, and rural development. In this context, medicinal plants serve as a strategic bridge between environmental responsibility and economically viable agribusiness models.

Keywords: MAPs, Endangered species, Sustainable agriculture, Plant conservation

INTRODUCTION

The increasing pressure on natural ecosystems from agricultural expansion and intensification, combined with global economic and environmental challenges, has underscored the urgent need for more sustainable agriculture practices that balance productivity with biodiversity conservation and ecosystem preservation (Dajic Stevanovic et al., 2012; Pereira et al, 2025). In this context, the EU Green Deal, particularly its Farm to Fork and Biodiversity Strategies, emphasizes the integration of environmentally responsible practices into agriculture while ensuring economic viability and rural development (Schippmann et al., 2002). Medicinal plant species represent a key component of the green transformation of agriculture, as their cultivation and sustainable use offer opportunities to link species conservation with market-oriented agriculture, ultimately contributing to both biodiversity preservation and economic development (Mofokeng et al., 2022).

Endangered Medicinal Plant Species with High Economic Value

Although the demand for medicinal plant species is increasing, as well as the awareness for their protection, many of them are endangered in their natural habitats, primarily due to habitat loss, overharvesting, and environmental degradation (Schippmann et al., 2002; Stanik et al., 2020; Prijić et al., 2024; Krstić et al., 2024). This highlights the delicate balance between wild harvesting and sustainable use. The European Red List of Medicinal Plants (European Commission & IUCN, European Red List of Medicinal Plants, IUCN 1993; Allen et al., 2014) assessed approximately 400 vascular taxa with documented medicinal uses. Species such as peony (*Paeonia* spp.); saffron (*Crocus* spp.); mountain arnica (*Arnica montana*), a widely used anti-inflammatory herb, is threatened by habitat loss and unsustainable harvesting; gentian (*Gentiana* spp.) long exploited for its bitter roots in digestive remedies and spirits, is reported in several national conservation assessments as being under pressure from overcollection exemplifying this dual role (Barata et al., 2016).

At the same time, these species possess high economic value across multiple sectors, including the pharmaceutical, cosmetic, food, and animal feed industries (Table 1), which makes them attractive candidates for sustainable cultivation and commercial development (Booker et al., 2012; Lubbe and Verpoorte, 2011). Currently, nearly 80% of the world's population relies primarily on plants and plant-derived products for healthcare. Global trade in medicinal and aromatic plants has expanded substantially over recent decades, rising from USD 2.4 billion in 1996 to USD 6.2 billion in 2013, with an average annual growth rate of 5.4% over 18 years and an accelerated growth rate of 10.7% in more recent years. The global herbal medicine market is projected to continue this upward trend, reaching approximately USD 129.7 billion by 2023, with a compound annual growth rate of 5.88% (Parvin et al., 2023).

Table 1. Endangered Medicinal Plant Species, Economic Value, and Possible Uses

Latine name	Common name	Conservation Status	Main Economic Uses	Reference
<i>Arnica montana</i>	Arnica	Endangered	Cosmetics, topical medicine	Melero et al., 2012
<i>Gentiana lutea</i>	Yellow gentian	Endangered	Food bitters, liqueurs, pharma	Pasdaran et al., 2023
<i>Valeriana officinalis</i>	Valerian	Vulnerable	Pharmaceuticals, animal feed	Bączek et al., 2022
<i>Paeonia</i> spp	peony	Protected	Pharmaceuticals, cosmetics	Prijić et al., 2024
<i>Melissa officinalis</i>	Lemon balm	Overharvested	Food, cosmetics, pharma	Gordanić et al., 2025
<i>Primula veris</i>	Cowslip	Protected	Herbal teas, syrups	Yankova-Tsvetkova et al., 2022
<i>Artemisia absinthium</i>	Wormwood	Declining	Repellents, veterinary use	Szopa et al., 2020
<i>Inula helenium</i>	Elecampane	Rare	Veterinary medicine, feed	Kenny et al., 2022
<i>Foeniculum vulgare</i> (wild)	Wild fennel	Protected	Food, animal feed, fungicide	Khaleil et al., 2021
<i>Angelica archangelica</i>	Garden angelica	Rare	Food, cosmetics, pharma	Nautiyal et al., 2006

Impact of Climate Change on the Endangerment and Conservation of Medicinal Plant Species

Climate change, manifested through rising temperatures, changed precipitation regimes, and an increasing frequency of extreme weather events, presents a significant threat to wild plant populations as well as conventional cultivation systems (Shruti et al., 2024). It is increasingly recognized as a critical factor influencing the endangerment and conservation of medicinal plant species by changing their habitat fitness, phenology, and population dynamics. An analysis of more than a century of temperature records from 15 meteorological stations across Serbia reveals a significant rise in minimum winter temperatures, accompanied by the occurrence of extremely warm and dry winters approximately once per decade. (Đorđević, 2008). Notably, during the past decade, such extremes have been recorded three times (2014, 2018, and 2024) (RHSS). Previous studies indicate that rising temperatures drive plant species to migrate to higher altitudes, where survival was previously constrained, and/or to shift northward from their current distributions in the Northern Hemisphere (Glick et al., 2001; Root et al., 2003). These climate-driven shifts pose a particular challenge for plant species with limited seed dispersal capacity and constant habitat loss, as well as species that require a combination of low temperatures for successful germination and/or flowering, such as *Paeonia* spp. (Prijic et al., 2024) and *Crocus* spp. (Krstić et al., 2024). In addition to distributional effects, climate change can modify secondary metabolite profiles (Sun et al., 2023), which are central to medicinal value, and have already been shown to alter phytochemical composition in other medicinal herbs under heat and drought stress (Bistgani et al., 2024).

Under these conditions, conservation through cultivation represents a climate-resilient strategy that reduces pressure on natural populations while supporting sustainable agricultural production. By carefully integrating medicinal plants into diversified cropping systems, it is possible to enhance ecological resilience, optimize soil use, and maintain high economic returns.

These ecological and biochemical impacts underscore the need for climate-adaptive conservation strategies, including *in situ* protection, *ex situ* germplasm banks, sustainable cultivation practices, and dynamic monitoring of phenology and chemical quality, to ensure the persistence and sustainable use of medicinal plant resources in Europe.

CONCLUSION

Balanced food and feed production, along with biodiversity conservation and environmental protection, represent one of the greatest challenges of the modern era. The intensification of agricultural production and climate change both contribute to biodiversity loss and the erosion of the genetic pool of natural resources. Medicinal plants provide a link between biodiversity conservation and economic development within the green transformation of agriculture. Their cultivation and sustainable use support the preservation of genetic resources, enhance agroecosystem resilience, and reduce pressure on wild plant populations. At the same time, medicinal plants offer high market value through pharmaceuticals, nutraceuticals, cosmetics, and functional foods, thereby creating new income opportunities for rural communities. Integrating medicinal plant production into

sustainable agricultural systems, therefore, contributes not only to environmental protection but also to long-term economic viability and social sustainability.

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INVASIVE WEEDS AT THE INTERFACE OF PLANT, ANIMAL AND HUMAN HEALTH: A ONE HEALTH PERSPECTIVE

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Abstract: Invasive weeds are increasingly being recognized as drivers of ecosystem degradation with long-term and cascading effects on animal and human health. Using a One Health perspective, this review synthesizes current knowledge about invasive weed species relevant to Serbia and Europe, highlighting their roles as sources of allergens and toxins, modifiers of ecosystems, and indirect health risk factors. Within the framework of the Common Agricultural Policy Strategic Plans, the importance of integrated and interdisciplinary management approaches is highlighted.

Keywords: Invasive alien plant species, Invasive weeds, One health, Ecosystem health, Common agricultural policy (CAP)

INTRODUCTION

Invasive alien plant species (IAPS) are increasingly recognized as one of the major drivers of biodiversity loss, ecosystem degradation, and functional disruption of natural and anthropogenic landscapes worldwide (Pyšek et al., 2020; Vilà et al., 2011). Their spread has been accelerated by globalization, intensified trade, land-use change, and climate change, allowing numerous non-native plant species to establish, spread, and exert ecological dominance far beyond their native ranges (Early et al., 2016). In agricultural and semi-natural ecosystems, invasive weeds represent a particular challenge due to their high adaptability, competitive ability, and capacity to interfere with crop production, ecosystem services, and environmental stability (Chen and Chen, 2019). While the ecological and economic impacts of invasive weeds have been widely documented, their implications for animal and human health remain comparatively underexplored and fragmented across disciplines (Schindler et al., 2015).

The One Health concept, which emphasizes the interconnectedness of ecosystem, plant, animal, and human health, and biodiversity, provides a comprehensive framework for addressing such complex and multi-dimensional challenges (Destoumieux-Garzón et al., 2018). Originally developed to improve coordination between human and veterinary medicine, One Health has evolved into a broader integrative approach that explicitly incorporates environmental and ecosystem health as foundational determinants of overall well-being (three of the most influential concepts at the moment, One Health, EcoHealth, and Planetary Health) (Lerner and Berg, 2017). Within this framework, invasive weeds can be viewed not merely as agricultural pests or ecological disruptors, but as active agents

influencing exposure pathways to allergens, toxins, bioactive compounds, and disease vectors, thereby affecting multiple components of the One Health triad simultaneously (Hulme, 2014).

Invasive weed species influence ecosystem health by altering plant community composition, reducing native biodiversity, modifying nutrient cycling, and disrupting ecosystem services such as pollination, soil stabilization, and water regulation (Vilà et al., 2011; Pyšek et al., 2012). Many invasive plants exhibit allelopathic effects, rapid growth, and high reproductive capacity, enabling them to outcompete native flora and create homogenized landscapes (Callaway and Ridenour, 2004). These ecological changes may cascade through trophic networks, affecting herbivores, pollinators, and microbial communities, with long-term consequences for ecosystem resilience and functionality (Schirmel et al., 2016). From a One Health perspective, such ecosystem-level alterations are critical, as degraded ecosystems are less capable of buffering environmental stressors and regulating biological risks (Destoumieux-Garzón et al., 2018).

The animal health dimensions of invasive weeds are particularly relevant in agricultural and pastoral systems. Numerous invasive plant species produce toxic secondary metabolites, including alkaloids, glycosides, phenolics, and latex compounds, which can pose direct risks to livestock and wildlife through ingestion or contact (Keeler et al., 2013; Stegelmeier et al., 2016). Contamination of forage and feed with invasive weed material may result in acute or chronic intoxication, reduced productivity, reproductive disorders, or mortality in domestic animals (Botha and Penrith, 2008). Additionally, invasive plants can modify habitats in ways that favor certain pest species or vectors, indirectly influencing the epidemiology of animal diseases (Hulme, 2014). Despite these risks, the veterinary and ecological implications of invasive weeds are often addressed separately, limiting the effectiveness of integrated risk assessment and management.

The human health impacts of invasive weeds are equally multifaceted and extend beyond direct toxicity. Certain invasive species are well-known sources of potent allergens, contributing to respiratory diseases, allergic rhinitis, and asthma, particularly in urban and peri-urban environments (Lake et al., 2016; Weger et al., 2016). Others produce bioactive compounds capable of causing dermatitis, poisoning, or adverse pharmacological effects following accidental exposure (Stegelmeier et al., 2016). Moreover, by reshaping ecosystems and agricultural practices, invasive weeds can indirectly influence food safety, air quality, and exposure to zoonotic pathogens (Hulme, 2014). These health effects are frequently underestimated in weed management strategies, which traditionally prioritize crop yield losses over broader societal and public health considerations (Bàrberi, 2019).

In Europe, and particularly in Southeast Europe, the spread of invasive weeds has been facilitated by agricultural intensification, land abandonment, infrastructure development, and climate variability (Essl et al., 2015). Serbia, located at the intersection of major biogeographical regions and characterized by diverse agroecosystems and urban–rural gradients, has experienced a notable increase in the presence and impact of invasive alien plant species (Vrbničanin et al., 2015). Species such as *Ambrosia artemisiifolia*, *Ailanthus altissima*, *Asclepias syriaca*, *Datura* spp., and others have become established across agricultural fields, ruderal habitats, forests, and urban areas, posing ecological, agronomic, and health-related challenges (IASV, 2011; Meseldžija et al., 2019; EPPO, 2026; DAISIE,

2026). While individual studies have addressed the biology, distribution, or management of selected invasive species in Serbia, a comprehensive synthesis of their implications within a One Health framework is still lacking.

Given these knowledge gaps, there is a clear need for an integrative review that brings together ecological, agricultural, veterinary, and public health perspectives on invasive weeds. Such a synthesis is particularly relevant for regions like Serbia, where invasive species pressures intersect with transitional agricultural systems, urban expansion, and evolving policy frameworks. By applying a One Health lens, invasive weeds can be repositioned from isolated management problems to indicators of systemic vulnerabilities at the interface of ecosystems, animals, and humans.

One Health Concept and the Role of Invasive Weeds

In recent years, One Health has gained increasing relevance in the context of global environmental change, biodiversity loss, and intensified agricultural systems. Degraded ecosystems are more susceptible to biological invasions, pathogen emergence, and altered exposure pathways to environmental hazards (Hoberg and Brooks, 2015). Consequently, environmental disturbances such as land-use change, habitat fragmentation, and invasive species spread are now recognized as critical determinants of health risks across all components of the One Health triad (Destoumieux-Garzón et al., 2018). Within this framework, invasive alien plant species, particularly invasive weeds, represent a compelling yet underappreciated One Health issue. Traditionally addressed primarily through agronomic or ecological lenses, invasive weeds also have profound implications for animal and human health, acting as biological, chemical, and ecological stressors within agroecosystems and urban environments (Schindler et al., 2015). Invasive weed species are capable of producing a wide range of secondary metabolites that serve ecological functions such as herbivore deterrence and competitive dominance but may pose significant health risks to animals and humans. (Keeler et al., 2013; Stegelmeier et al., 2016). From a human health perspective, invasive weeds are important sources of airborne allergens, particularly pollen, which can exacerbate allergic rhinitis, asthma, and other respiratory conditions. Species with prolonged flowering periods, high pollen production, and strong dispersal capacity contribute disproportionately to allergen exposure, especially in urban and peri-urban settings (Lake et al., 2016). Climate change further amplifies these effects by extending growing seasons and increasing pollen loads, thereby intensifying public health burdens associated with invasive allergenic plants (Bielory et al., 2012).

In addition to allergens and toxins, invasive weeds may function as reservoirs or facilitators of pathogens and pests. By altering habitat structure and microclimatic conditions, invasive plants can support populations of insects, rodents, and microorganisms that act as vectors or hosts of infectious agents (Hulme, 2014). Despite these documented risks, invasive weeds are rarely incorporated into formal health risk assessments, which tend to focus on pathogens, chemical pollutants, or zoonotic agents. The One Health framework underscores the need to broaden this perspective and recognize invasive plants as contributing factors to cumulative health risks at the human-animal-environment interface (Destoumieux-Garzón et al., 2018).

Beyond their direct health implications, invasive weeds exert profound effects on biodiversity and ecosystem stability, which in turn influence long-term health outcomes. Invasive plants frequently outcompete native species, reduce habitat heterogeneity, and simplify plant community structure, leading to declines in native flora and associated fauna (Vilà et al., 2011; Pyšek et al., 2012). These changes can disrupt trophic interactions, pollination networks, and soil microbial communities, undermining ecosystem resilience.

Allelopathic interactions represent an additional mechanism through which invasive weeds influence native plant communities and crop species, with cascading effects on ecosystem and One Health outcomes. Many invasive species release secondary metabolites that inhibit germination, growth, and establishment of neighboring plants, promoting their own dominance while suppressing native flora and economically important crops (Callaway and Ridenour, 2004; Pyšek et al., 2012; Vilà et al., 2011). Species such as *Ailanthus altissima* (Mill.) Swingle and *Reynoutria japonica* Houtt. are particularly effective in altering plant community composition through allelopathy, reducing habitat heterogeneity and forage availability. These effects indirectly impact animal and human health by limiting nutritious resources for livestock and wildlife, increasing exposure to toxic or allergenic plant species, and potentially prompting higher herbicide use or altered agricultural practices that affect environmental quality (Keeler et al., 2013; Stegelmeier et al., 2016; Bårberi, 2019).

Although the One Health concept provides a robust theoretical framework, its application to invasive weed management remains limited, particularly at regional and national scales. In many countries, including Serbia, invasive weeds are primarily addressed through agronomic control measures, with insufficient consideration of their broader ecological and health-related implications. This disconnect highlights the need for region-specific syntheses that integrate ecological evidence, health risks, and policy contexts.

Invasive Weeds in Serbia: A One Health-Oriented Overview

The presence and spread of invasive alien plant species (IAPS) in Serbia represent a growing ecological, agricultural, and public health concern. Systematic efforts to identify and classify invasive plant species in the country began at the regional level, with the development of the list of invasive alien species for the Autonomous Province of Vojvodina (IASV, 2011), followed by the publication of the preliminary national list of invasive plant species in the Republic of Serbia by Lazarević et al. (2012). This national list, conceived as a foundational document to support future legislative acts, linked species identification with general control and management measures and marked a significant step toward coordinated invasive species governance (Table 1).

A comprehensive national monograph on invasive weeds in Serbia, covering invasion processes, ecological and genetic potential, pathways of introduction, spread, risk assessment, impacts, and mapping, was published by the Herbological Society of Serbia, offering strategic guidance for invasive plant management and directions for future research (Vrbničanin, ed., 2015).

Subsequent revisions and comparative analyses further refined the understanding of invasive plant diversity in Serbia. Notably, Stojanović and Jovanović (2018) conducted a comprehensive revision of the preliminary national list, incorporating a regional

perspective by comparing invasive plant species recorded in Serbia with those documented in eight neighboring countries (Slovenia, Croatia, Bosnia and Herzegovina, Montenegro, North Macedonia, Bulgaria, Romania, and Hungary). Using *The Plant List: A Working List of All Known Plant Species* as a taxonomic reference, the authors identified a total of 165 invasive alien plant species across Serbia and the surrounding region. Their analysis highlighted substantial variability in the criteria used to designate invasiveness among countries, underscoring the context-dependent nature of biological invasions and the challenges of harmonizing regional management strategies (Stojanović and Jovanović, 2018).

In Serbia, invasive weeds are predominantly associated with agricultural land, ruderal habitats, river corridors, transportation infrastructure, and urban and peri-urban environments, reflecting the major pathways of introduction and spread. These pathways include contaminated crop seed material, agricultural machinery, trade and transport, horticultural activities, and intentional introductions followed by escape into natural or semi-natural ecosystems. Such habitats are characterized by frequent disturbance and high levels of human and animal activity, increasing the likelihood of exposure and amplifying the relevance of invasive weeds within a One Health context.

From an ecosystem perspective, invasive weeds in Serbia contribute to biodiversity loss, habitat homogenization, and reduced ecosystem stability, often through rapid growth, allelopathic interactions, and high reproductive capacity. Species such as *Ailanthus altissima* (Mill.) Swingle and *Reynoutria japonica* Hoult. are known for their strong competitive abilities and capacity to dominate disturbed and semi-natural habitats, leading to displacement of native vegetation and long-term alteration of ecosystem processes. These ecological impacts indirectly affect animal and human health by weakening ecosystem services that regulate environmental risks and support resilient landscapes.

In terms of animal and human health, several invasive weed species present in Serbia produce toxic or bioactive secondary metabolites, allergenic pollen, or other compounds of concern. *Asclepias syriaca* L. produces toxic latex containing cardiac glycosides, posing risks to livestock and potentially wildlife, while *Ailanthus altissima* (Mill.) Swingle has been associated with allergenic reactions and contact dermatitis in humans. *Helianthus annuus* L., although widely cultivated, can exhibit invasive behavior in certain agroecosystems, acting as a volunteer weed that alters crop rotations and facilitates pest and pathogen persistence (Stojićević, 2020).

Table 1. Selected invasive or potentially invasive weed species in Serbia with relevance to One Health

Species	Typical habitats	Key One Health relevance
<i>Ailanthus altissima</i>	Urban, peri-urban, forests	Allergenicity, contact dermatitis, strong allelopathy, biodiversity loss
<i>Asclepias syriaca</i>	Agricultural land, grasslands	Livestock risk (toxic), ecosystem alteration
<i>Ambrosia artemisiifolia</i>	Crop lands, urban areas	Highly allergenic pollen, respiratory diseases
<i>Reynoutria japonica</i>	Riparian zones, disturbed sites	Habitat domination, ecosystem instability
<i>Helianthus annuus</i>	Agricultural fields	Agroecosystem disruption, pest and pathogen persistence

Invasive Weeds as Biological Stressors in One Health Systems

Within the One Health framework, invasive plants are increasingly recognized not only as drivers of biodiversity loss and agricultural disruption, but also as contributors to cumulative health risks through allergen production, toxic exposure, and ecosystem-mediated disease dynamics (Destoumieux-Garzón et al., 2018). In this sense, invasive weeds function as biological stress multipliers, intensifying existing vulnerabilities linked to land-use change, climate variability, and socio-economic factors (Romanelli et al., 2015).

One of the most well-documented mechanisms linking invasive weeds to human health is the production and dispersal of allergenic pollen and bioactive secondary metabolites. *Ambrosia artemisiifolia* L. represents a paradigmatic example, producing highly allergenic pollen that is strongly associated with allergic rhinitis and asthma, even at low airborne concentrations (Weger et al., 2016). The spread of this species across agricultural and urban landscapes has led to prolonged pollen seasons and increased sensitization rates in exposed populations, particularly in Central and Southeast Europe (Šikoparija et al., 2006; Smith et al., 2013).

Species such as *Datura* spp. produce tropane alkaloids (atropine and scopolamine), which can cause severe poisoning following accidental ingestion by livestock or contamination of food and feed (Konstantinović and Meseldžija, 2007). *Asclepias syriaca* contains cardiac glycosides in its latex and tissues, posing a documented risk to grazing animals and potentially to wildlife species unfamiliar with its chemical defenses (DiTomaso et al., 2017).

Beyond direct allergenic and toxic effects, invasive weeds act as drivers of indirect health risks by modifying habitat structure and ecological interactions. Dense monospecific stands of invasive plants, such as *Reynoutria japonica*, alter light availability, soil properties, and microclimatic conditions, leading to reduced native plant diversity and simplified food webs (Vilà et al., 2011).

Altered vegetation structure may create favorable conditions for certain insects, such as mosquitoes or ticks, by providing shelter, stable humidity, or alternative nectar sources. Changes in plant community composition have been shown to affect vector population dynamics and pathogen transmission potential, thereby linking invasive plants to zoonotic disease risks through ecosystem-mediated pathways (Allan et al., 2010).

Similarly, invasive weeds can influence microbial communities in soil and plant-associated environments. Through root exudates and allelopathic compounds, invasive plants may reshape soil microbial assemblages, potentially affecting nutrient cycling and the persistence of plant and animal pathogens (Inderjit and van der Putten, 2010). Such changes can indirectly impact crop health, livestock exposure, and food safety.

Integrating One Health into the Management of Invasive Weeds: Policy and Strategic Perspectives

Effective management of invasive weeds requires approaches that simultaneously address ecological integrity, animal health, and human well-being. Despite this, it is still

predominantly framed within sectoral policies, with limited integration of health-related considerations into agricultural and environmental decision-making (Destoumieux-Garzón et al., 2018).

At the European level, invasive alien species are addressed through a combination of biodiversity, agricultural, and phytosanitary policies, including Regulation (EU) No 1143/2014 on the prevention and management of the introduction and spread of invasive alien species. However, health dimensions particularly those relevant to the One Health concept are often treated implicitly rather than explicitly. Strategic planning instruments such as the Common Agricultural Policy (CAP) Strategic Plans provide a potential entry point for integrating One Health principles into invasive weed management, especially in countries with extensive agricultural landscapes and high exposure of humans and animals to invasive plants.

CAP Strategic Plans emphasize sustainability, ecosystem services, and risk reduction in agricultural systems, creating opportunities to incorporate invasive weed control as a cross-cutting priority. Measures related to agri-environment-climate commitments, eco-schemes, and rural development can indirectly mitigate One Health risks by promoting diversified cropping systems, reduced disturbance, and improved habitat quality. By limiting the establishment and spread of invasive weeds, such measures may reduce allergenic pollen loads, toxic plant exposure to livestock, and habitat conditions favorable to disease vectors (European Commission, 2026).

In Serbia, although not an EU Member State, alignment with EU policies through the accession process and national strategic planning offers a framework for adopting integrated approaches to invasive weed management. Existing national lists of invasive plant species and proposed control measures (Lazarević et al., 2012; Stojanović and Jovanović, 2018) provide a scientific foundation, but their translation into practice remains uneven. Embedding invasive weed management within broader strategies for agricultural sustainability, biodiversity conservation, and public health would strengthen coherence and effectiveness.

From a One Health perspective, prioritization of invasive weeds should extend beyond their economic impact on crop yields to include indicators such as allergenic potential, toxicity to animals, and capacity to alter ecosystem processes linked to disease regulation.

Integrated management also requires cross-sectoral cooperation among agricultural authorities, environmental agencies, public health institutions, and research organizations. Surveillance systems that combine ecological monitoring with health data such as pollen counts, poisoning incidents, or vector abundance can enhance early warning and response capacity. Such systems are consistent with the One Health paradigm and can inform adaptive management under changing climatic and land-use conditions (Hueston et al., 2013; Zinsstag et al., 2020).

Overall, incorporating One Health principles into invasive weed policy and management frameworks offers a pathway toward more holistic and preventive strategies. By recognizing invasive weeds as indirect vectors of health risk and ecosystem degradation, policymakers and practitioners can move beyond reactive control toward proactive,

integrated solutions. This synthesis underscores the need for harmonized criteria, science-based prioritization, and strategic alignment between invasive species management and broader agricultural and health policies, particularly in regions such as Southeast Europe where ecological, agricultural, and health systems are tightly interconnected.

CONCLUSION/FUTURE PERSPECTIVES

The evidence synthesized in this review confirms that invasive weeds represent a multifaceted challenge situated at the intersection of ecosystem integrity, animal health, and human well-being. Their impacts extend far beyond agronomic or conservation concerns, encompassing allergenic exposure, toxicological risks, and ecosystem-mediated pathways that influence disease dynamics and environmental resilience. Within this context, the One Health framework provides a scientifically robust and conceptually coherent approach for understanding and managing invasive weeds as integrated components of socio-ecological-health systems rather than isolated biological stressors.

A key insight emerging from this synthesis is that the consequences of invasive weed spread are often cumulative and synergistic, manifesting through feedback loops between degraded ecosystems, altered species interactions, and increased exposure of humans and animals to allergens, toxins, and pathogens. Such processes are particularly pronounced in agricultural and peri-urban landscapes, where frequent human–animal–environment interactions amplify One Health risks. Recognizing invasive weeds as indirect vectors of health risk reinforces the need to shift from reactive, sector-specific control measures toward preventive, ecosystem-based management strategies.

Despite growing international recognition of the One Health concept, significant knowledge gaps remain, especially in Southeast Europe and the Western Balkans. Data on the health-related impacts of invasive weeds in this region are fragmented, unevenly distributed, and often limited to local case studies or gray literature. Quantitative assessments linking invasive plant abundance with health indicators such as allergen exposure, livestock poisoning, or vector-borne disease risk are particularly scarce. This lack of region-specific, integrative data constrains evidence-based prioritization and limits the transferability of management approaches developed in other biogeographical contexts.

Another critical gap lies in the insufficient integration of ecological, veterinary, and public health research. Invasive weed studies are still predominantly conducted in a fragmented disciplinary manner, focusing either on biodiversity impacts, crop losses, or species distribution, with limited attention to cross-domain interactions. Addressing this limitation requires interdisciplinary and transdisciplinary research designs that combine plant ecology, toxicology, epidemiology, veterinary science, and socio-economic analysis. Such approaches are essential for capturing indirect pathways of risk and for evaluating the full spectrum of One Health outcomes associated with invasive weeds.

Looking ahead, future research should prioritize the development of harmonized assessment frameworks that explicitly incorporate health-related indicators into invasive species risk analysis. Long-term monitoring programs that integrate vegetation surveys with health and exposure data such as pollen monitoring, livestock health records, and vector surveillance would substantially enhance early warning and management capacity.

In parallel, policy instruments and strategic planning frameworks, including agricultural and biodiversity strategies aligned with the Common Agricultural Policy, offer opportunities to operationalize One Health principles at national and regional levels.

In conclusion, advancing invasive weed management through a One Health lens is not only scientifically justified but increasingly necessary in the face of accelerating biological invasions, land-use change, and climate-driven pressures. By acknowledging invasive weeds as integrative risk factors and investing in interdisciplinary knowledge generation, particularly in underrepresented regions such as the Balkans, future efforts can move toward more effective, preventive, and sustainable solutions that protect ecosystems, animals, and human health simultaneously.

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CARBON DIOXIDE WASTE UTILIZATION IN AGRICULTURE

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Abstract: Carbon dioxide (CO₂) waste utilization is part of a broader strategy known as carbon capture, utilization, and storage (CCUS), which aims to reduce greenhouse gas emissions by transforming captured CO₂ into products rather than storing it. This method showcases a circular economy by reusing CO₂ captured from waste sources, helping to reduce the costs of carbon capture and promote sustainability in different industries. Carbon dioxide is vital in agriculture, aiding photosynthesis, boosting plant growth, and supporting sustainable farming. The exploration of innovative CO₂ utilization pathways, such as ensiling plants on farms, as well as many other innovations, gives the potential to create valuable products and promote sustainable agriculture.

Keywords: Sustainability, Carbon capture, Carbon removal, Circular economy, Farming

INTRODUCTION

Carbon dioxide plays a dual role on the planet: positive and negative. It helps maintain Earth's balance by trapping some of the radiant energy received, keeping the planet warm enough to support life. Without it, Earth would be uncomfortably cold (Eldesouki et al., 2023). As the unique atmospheric source of carbon, CO₂ strongly affects crop yield and quality, and daytime CO₂ deficiency in greenhouses often limits crop productivity (Wang et al., 2022). However, rising atmospheric CO₂ levels are intensifying global warming. In the face of a changing climate, intensive efforts are needed to limit the global temperature increase to 1.5 °C. Agricultural production has the potential to play an important role in mitigating climate change (Borchers et al., 2022).

On the one hand, agriculture contributes to climate change, and on the other hand, it is acutely affected by its effects (Borchers et al., 2022). Changes in climatic and weather conditions Borchers et al., (2022) point that may contribute to a decrease in the yield of crops, among others, as a result of an increase in the frequency and intensity of extreme weather phenomena, drought, unstable wintering conditions for plants, the intensification of the harmfulness of pests, and the spread of invasive alien species (Kundzewicz et al., 2017; Graczyk et al., 2020). The negative impact of climate change also affects livestock

production, causing heat stress in animals during heat waves, increasing the risk of diseases, and reducing the availability of animal feed (Rojas-Downing et al., 2017).

Carbon Dioxide Waste Utilization

CO₂ waste utilization refers to the process of capturing and using carbon dioxide (CO₂) from waste streams to create valuable products or services. This practice is part of a broader strategy known as carbon capture, utilization, and storage (CCUS), which aims to reduce greenhouse gas emissions by transforming captured CO₂ into products rather than storing it. This method showcases a circular economy by reusing CO₂ captured from waste sources, helping to reduce the costs of carbon capture and promote sustainability in different industries.

According to the International Energy Agency (2025), key applications of CO₂ utilization include:

- Sustainable building materials in the construction sector,
- Renewable fuels for the transportation industry,
- Chemical production for synthesizing polymers and fuels,
- Enhanced oil recovery in the oil and gas industry,
- Food security initiatives in agriculture.

To help offset costs, captured CO₂ can be reused to create valuable products rather than being stored solely. This method, known as carbon recycling, is part of the broader carbon capture, utilization, and storage (CCUS) framework, which aims to reach net-zero emissions by 2050 and address climate change (Endress and Houser Company, 2025). Currently, industry emits about 45 million metric tons of CO₂ annually from waste exhaust streams, accounting for roughly 0.1% of global emissions across all sectors (Liebling et al., 2025). Climate models from the Intergovernmental Panel on Climate Change and the International Energy Agency project CCUS could capture up to 1 billion metric tons of CO₂ annually by 2030, and several billion tons by 2050 (International Energy Agency, 2005). Assuming emissions from industrial and other sources remain roughly the same when this capacity is fully operational, these projections suggest it could significantly reduce atmospheric greenhouse gases (World Resources Institute, 2025) (Figure 1).

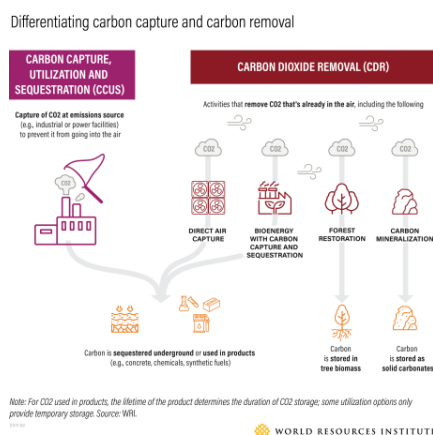


Figure 1. Differentiating Carbon Capture and Carbon Removal, World Resources Institute, 2025

While CCUS and carbon removal differ in where they collect CO₂, both processes require a designated site to store the captured carbon. This captured CO₂ whether collected from emission sources or directly from the atmosphere can be deposited underground in specific geological formations for permanent sequestration, according to the World Resources Institute (2025). Alternatively, it can be used to produce materials like concrete, chemicals, and synthetic fuels. The length of sequestration varies in these cases: for example, CO₂ from synthetic fuels is released upon combustion, whereas CO₂ from concrete is stored permanently.

CCUS is one of many ways to reduce emissions and plays a different role from carbon removal in long-term and net-zero climate plans developed by countries or companies. Emissions reductions including CCUS and many other options should make up the vast majority of mitigation in those plans. However, carbon removal can be used to counterbalance a much smaller portion of emissions (both CO₂ and other greenhouse gases) that are too hard to abate with other means. In the longer term, carbon removal is also needed to achieve and sustain net-negative emissions to reduce the excess CO₂ in the atmosphere that is causing harmful climate impacts.

Recent reports indicate that there are approximately 50 operational CCUS projects worldwide, with around 44 currently under construction and over 500 in various planning stages (CCUS Projects Database, 2025). These active projects capture roughly 50 million metric tons of CO₂ annually (MtCO₂/yr) (International Energy Agency, 2025). If all projects in development reach completion, the estimated total CCUS capacity could range between 416 and 520 MtCO₂/yr., representing about 0.9 to 1.1% of current global greenhouse gas emissions (Global CCS Institute, 2025).

Carbon Dioxide Uses in Agriculture

Carbon dioxide is increasingly seen as a valuable resource with economic potential. Although converting CO₂ into products is still emerging, it provides a promising way to reduce emissions and combat climate change. Captured CO₂ can be converted into fuels, carbonates, polymers, and chemicals, thereby supporting a circular economy. Use our expertise and diverse products to improve your CO₂ utilization. Carbon dioxide plays a crucial role in the food and beverage industry and in agriculture by enhancing product quality, extending shelf life, and appealing to consumers. As there is a growing push for sustainable practices, capturing and reusing CO₂ presents a dual benefit: lowering emissions and boosting operational efficiency. Carbon dioxide is vital in agriculture, aiding photosynthesis, boosting plant growth, and supporting sustainable farming. The central involvement of CO₂ in agriculture is:

1. Photosynthesis and plant growth

CO₂ is essential for photosynthesis, the process by which plants and microbes convert light energy into chemical. During photosynthesis, plants and lithotrophic microbes absorb CO₂ from the atmosphere and use it to produce glucose and oxygen. Optimal CO₂ levels for photosynthesis range between 800 and 1200 ppm, which can significantly enhance plant growth and crop yields (Hortisensors, 2025). Plants respond positively to CO₂ levels up to 700 to 1800 parts per million, but levels above this may damage them (Figure 2).

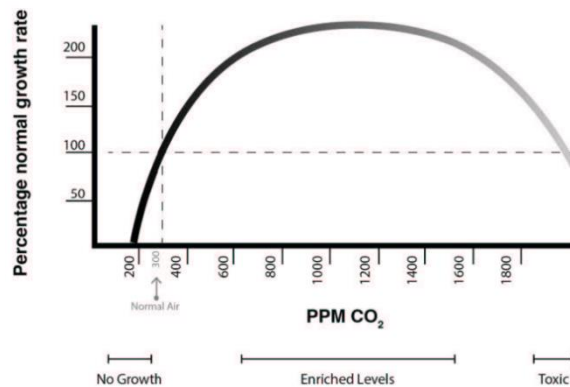


Figure 2. The relation between CO₂ concentration and the rate of plant growth.
Source: www.hydrofarm.com

2. CO₂ Fertilization effect

The phenomenon known as CO₂ fertilization leads to increased growth and yields in crops like corn and wheat due to higher CO₂ levels, Kurt Thelen (2023).

3. Carbon sequestration and soil health

Agricultural practices can capture atmospheric CO₂ in soil through methods like no-till farming, cover cropping, and crop rotation, which enhance soil health and increase carbon content (Johnson, 2026). By implementing these techniques, farmers help lower greenhouse gas emissions and improve soil fertility.

4. Monitoring and management of CO₂ levels

Farmers can utilize CO₂ sensors to track CO₂ levels in greenhouses and animal enclosures. Keeping CO₂ at optimal levels is essential for promoting healthy plant development and maintaining animal well-being. Carbon capture and storage (CCS) can be used to control CO₂ emissions from farming activities, enabling the reuse of captured CO₂ to support plant growth in controlled settings (Johnson, 2026).

5. Sustainable practices and innovations

Innovative agricultural methods, such as precision and regenerative farming, aim to optimize CO₂ levels and reduce emissions. These techniques improve productivity while supporting environmental sustainability by reducing the farming sector's carbon footprint. The invention of a new method and the application of CO₂ to the preservation of animal feed are inventive elements in the process of ensiling plants (Ivetić, 2015). This part makes a big difference in the commercial appeal of the idea of using additives. It represents an important and valuable invention that is easy to use, inexpensive, and safe.

Using CO₂ Waste in Agriculture

Agricultural waste can be transformed into a valuable byproduct from farming operations. It offers opportunities for sustainable agriculture, renewable energy, and environmental protection. Agricultural sustainability is a core element of the fourth industrial revolution, characterized by the use of novel technologies to reuse waste as a byproduct (Ivetić et al., 2024). However, traditional disposal methods still pose problems, causing air pollution and soil deterioration (Iftikhar et al., 2025). Using CO₂ waste in farming is a vital element

of sustainable practices. Employing CO₂ waste in agriculture can improve crop yields and quality, while also tackling environmental issues.

Main points on CO₂ waste use in agriculture:

- CO₂ enrichment in greenhouses involves increasing CO₂ levels, which are often limited during daytime and can impact crop yields. Technologies such as agro-industrial symbiosis systems (AIS), carbon capture and utilization (CCU) support agricultural output and promote environmental sustainability (Wang et al., 2022).
- Sustainable recycling of agricultural waste involves managing crop residues, animal manure, and processing byproducts to ensure long-term environmental health. Each type has unique features and opportunities for sustainable management and use (Sharma et al., 2024). New methods, such as biogas production and environmental enzyme technology, are being developed to transform agricultural waste into valuable resources. These techniques support low-carbon growth, aid green energy transitions (Liu et al., 2024; Chen et al., 2025), integrate agricultural practices with global efforts toward carbon neutrality, and foster innovation in materials science. Liu et al. (2024) propose an integrated process for the co-production of cellulosic ethanol and microalgal biomass by fixing CO₂ generated from bioethanol fermentation. The techno-economic analysis shows that the integrated process is cost-effective for producing cellulosic ethanol, and this study introduces an innovative method for advancing a low-carbon circular bioeconomy.
- Sustainable management and use of agricultural waste involve converting crop residues and animal manure significant farming byproducts into valuable resources such as bioenergy, biochar, and other products. This approach enhances soil health, water retention, and nutrient availability while also sequestering carbon (Iftikhar et al., 2025).
- Carbon capture technologies are used to improve CO₂ utilization in food production, helping to lower greenhouse gas emissions from industry. These methods encompass carbon sequestration, CO₂ supplementation, and renewable energy sources on farms integration (Gabell, 2025). In recent years, activated carbons (Acs) derived from agro-waste have demonstrated excellent adsorption capacity. The production of ACs from readily available, low-cost agro-waste makes them unique materials for several environmental applications, including but not limited to CO₂ capture, dye removal, and heavy metal ion removal by adsorption (Koli et al., 2024).
- Carbon capture strategies in agriculture include improved soil management, maximizing photosynthesis, and creating biochar. These approaches support a balanced carbon cycle and boost soil health and productivity (Patel, 2025).

Agricultural production generates significant amounts of waste that can be reused as byproducts, with positive environmental impacts (Ivetić et al., 2024; Ivetić et al., 2022). These strategies not only address environmental challenges but also provide economic benefits by creating valuable products and reducing reliance on fossil fuels. Adopting sustainable practices makes agriculture more responsible and sustainable. Sustainable development is fundamental to the economic policies of many countries, especially in developing economies. With multidisciplinary support, existing CO₂ enrichment systems

can address current and emerging issues, turning the efficient use of agricultural waste carbon and CO₂ in greenhouses into a sustainable solution to enhance food security and fight global warming (Wang et al., 2022). Understanding carbon sequestration mechanisms is essential for harnessing the full potential of agricultural methods to mitigate climate change (Patel, 2025). The exploration of innovative CO₂ utilization pathways, including chemical, biological, and mineralization processes, underscores the potential to create valuable products and realize substantial economic and environmental benefits (Bo et al., 2025; Hanson et al., 2025). Systems such as photosynthesis, soil carbon storage, biochar production, cover cropping, direct air capture, soil amendments, enhanced weathering, and feed ensiling can form the basis of various agricultural approaches to capture and store atmospheric CO₂.

CONCLUSION

CO₂ plays a crucial role in agriculture by supporting plant growth, increasing crop yields, and fostering sustainable farming through innovative techniques and effective management. When farmers understand and utilize CO₂ properly, they can boost productivity while tackling environmental issues. Repurposing CO₂ waste presents a promising strategy to address climate change and support a circular economy. Turning CO₂ into valuable products allows agriculture to lower its carbon footprint and move toward greater sustainability.

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INTEGRATING AGROFORESTRY AND LIVESTOCK FOR CLIMATE-RESILIENT AGRIBUSINESS

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Abstract: This review examines the integration of agroforestry and livestock systems as a strategy for climate-resilient and sustainable agribusiness. These systems enhance ecosystem services, including soil and water conservation, biodiversity, and carbon sequestration, while producing high-quality plant and animal products. Technological innovations and precision management optimize resource use, reduce environmental impacts, and improve farm-level resilience, while integrated systems also support rural livelihoods, employment, and knowledge transfer.

Keywords: Agroforestry, Animal production, Sustainable agriculture, Climate resilience, Precision agriculture

INTRODUCTION

Agroforestry is broadly defined as a land-use system in which woody perennials such as trees and shrubs are deliberately integrated with agricultural crops and or livestock on the same land unit in spatial and temporal arrangements that generate functional interactions among components (FAO, 2011; Nair et al., 2021). This intentional integration, encompassing practices such as silvopasture (trees with livestock), agrisilviculture (trees with crops), and agrosilvopasture (trees with both crops and livestock), leverages complementary ecological processes to diversify production and enhance system resilience, productivity, and sustainability (FAO, 2011; Nair et al., 2021; Mosquera-Losada et al., 2005). The inclusion of livestock within agroforestry systems is not a peripheral option but an essential dimension of multifunctional land management, fostering nutrient cycling, improving fodder availability, and promoting ecological balance in pasture and mixed production landscapes (FAO, 2011; Jamnadass et al., 2013).

Contemporary agriculture operates under intensifying pressures from climate change, soil degradation, biodiversity loss, and greenhouse gas emissions. Climatic extremes, including increased temperature variability, higher drought frequency, and erratic rainfall patterns, threaten crop yields and pasture productivity at the global scale (FAO, 2019; New Climate Institute, 2020). Simplified and monocultural production systems have been shown to exacerbate soil erosion and degradation, weaken ecosystem services, and reduce biological diversity compared with diversified land-use systems (Jamnadass et al., 2013; Bhandari et

al., 2025). Furthermore, agriculture contributes substantially to global greenhouse gas emissions, with livestock production accounting for a major share of methane and nitrous oxide emissions from agricultural activities, while conventional tillage practices further increase carbon losses from soil organic matter (FAO, 2019; New Climate Institute, 2020). These combined pressures underscore the need for transformative strategies that reconcile food production with environmental stewardship.

In this context, integrated agroforestry-livestock systems offer a promising pathway to advance sustainable and climate-resilient agribusiness. By combining woody perennials with pastures and animal production, silvopastoral and agrosilvopastoral systems enhance soil structure, increase soil organic carbon stocks through biomass inputs, and contribute to carbon sequestration in both vegetation and soil (FAO, 2011; Hess, 2025; Bhandari et al., 2025). Tree cover in such systems creates beneficial microclimates that moderate temperature extremes and wind stress on crops and livestock, while diversified fodder resources support more stable animal productivity under climatic variability (Mosquera-Losada et al., 2005; García de Jalón et al., 2018). Additionally, the complementarity between trees, crops, and livestock improves whole-system nutrient cycling and reduces reliance on synthetic inputs, contributing to lower emissions intensity compared with specialized production systems (Jamnadass et al., 2013; Varijakshapanicker et al., 2019).

Despite robust evidence for ecological and productivity benefits, the implementation of integrated agroforestry-livestock systems remain constrained by barriers related to technical knowledge, policy frameworks, and economic incentives (FAO, 2011; Bhandari et al., 2025), highlighting the need for research that situates agroforestry-livestock integration within broader sustainability strategies. This review synthesizes the current scientific literature on agroforestry and livestock integration, focusing on definitions and conceptual frameworks, global agricultural challenges, mechanisms through which integrated systems confer resilience and sustainability, and research priorities to support adoption across diverse agrarian contexts. By examining these dimensions, the paper aims to illustrate the multifaceted contributions of agroforestry with livestock to sustainable and climate-resilient agribusiness development.

BIOTECHNOLOGICAL AND GENETIC INNOVATIONS IN AGROFORESTRY AND LIVESTOCK SYSTEMS

Genetic and biotechnological innovations are necessary for enhancing the resilience, productivity, and sustainability of integrated agroforestry and livestock systems. In the context of climate change and increasing environmental stressors, targeted improvement of both plant and animal genetic resources could enable systemic adaptation and support multifunctional production.

The application of genetically resilient plant varieties and livestock breeds is foundational to improving stress tolerance and productivity in agroforestry-livestock landscapes. Genetic diversity within crops and livestock enhances the adaptability of production systems to variable environmental conditions, stabilizing yields and supporting ecosystem functions (Casadebaig et al., 2014). In crop systems, breeding for stress-adaptive traits such as drought tolerance, heat stress resilience, and pest resistance is increasingly facilitated through advanced molecular tools, including genomic selection and marker-assisted

breeding. These approaches accelerate the development of cultivars capable of maintaining performance under abiotic stress, thereby supporting sustainable outputs in polycultural systems such as agroforestry. For livestock, genetic improvement and breed diversification enhance adaptive capacity to climatic stressors, disease exposure, and feed variability. The integration of indigenous and locally adapted genetic resources supports selection for traits such as thermo-tolerance, metabolic efficiency, and disease resistance, improving resilience and productivity (Boettcher et al., 2015). Transcriptomic and genomic analyses further elucidate adaptive mechanisms at the molecular level, providing molecular markers for precision breeding programs targeting climate resilience (Shashank et al., 2024).

In addition to genetic improvement, biotechnological manipulation of soil and animal microbiota offers significant benefits for plant and animal health. Plant growth-promoting rhizobacteria (PGPR) represent a class of beneficial microorganisms that colonize the rhizosphere and enhance plant growth through multiple mechanisms, including increased nutrient availability, phytohormone production, and pathogen suppression (Aloo et al., 2022; De Andrade et al., 2023; Shahzad et al., 2025). PGPR-based biofertilizers contribute to sustainable agriculture by improving plant nutrient uptake and tolerance to abiotic stress while reducing reliance on synthetic fertilizers (De Andrade et al., 2023; Shahzad et al., 2025). These microbial inoculants support nutrient cycling and soil fertility, directly influencing the productivity of agroforestry systems by enhancing the growth of both annual crops and perennial trees. In livestock systems, probiotics and microbiome-based supplements modulate gut health, improve feed efficiency, and support immune function, contributing to improved nutrient utilization and reduced environmental impacts.

The development of functional agroforestry-livestock systems that optimize the nutritional value of agricultural products while mitigating environmental impacts relies on the integration of genetic and microbial biotechnologies. In plant components of agroforestry systems, enhanced nutrient profiles and stress mitigation achieved through PGPR and biofertilizers support the production of high-quality food and feed while minimizing negative externalities associated with conventional inputs. In livestock systems, genetic improvement and probiotic-based strategies enhance product quality, such as meat and milk composition, and improve system efficiency, contributing to lower environmental footprints per unit of output (Varijakshapanicker et al., 2019; Bhandari et al., 2025). Collectively, these integrated biotechnological approaches support a transition toward eco-intensified agricultural landscapes that are both productive and environmentally sustainable.

DIGITAL TRANSFORMATION AND PRECISION MANAGEMENT

Digital transformation and precision management technologies are reshaping modern agribusiness by enabling real-time monitoring, data-driven decision-making, and optimized resource use. These innovations, anchored in IoT sensors, GIS mapping, unmanned aerial vehicles (UAVs or drones), and advanced analytics, enhance the efficiency and sustainability of integrated crop and livestock systems.

Applications of IoT sensors, GIS technologies, and unmanned aerial vehicles enable comprehensive monitoring of crops, soil conditions, and animal health within integrated agricultural systems. Internet of Things devices deployed in fields collect data on soil

moisture, temperature, nutrient status, and microclimate, which are transmitted to cloud or edge computing platforms for analysis. The integration of real-time data streams allows monitoring of plant growth and early detection of stress or disease, enabling timely management interventions (Soussi et al., 2024; Ronzhin et al., 2025). Geographic Information Systems complement sensor networks by providing spatial analysis and mapping layers that contextualize field-level data across landscapes, supporting precise decision-making for land management and resource allocation (Ronzhin et al., 2025).

Unmanned aerial vehicles equipped with multispectral and thermal sensors further enhance monitoring capabilities by capturing high-resolution imagery of crop vigor, soil variability, and water stress patterns at field scale (Padhiary et al., 2025). In livestock systems, wearable IoT devices and low-power communication frameworks, such as LoRa-based architectures, are increasingly applied to monitor animal location, health status, and environmental exposure, transforming traditional herd management into data-driven smart livestock systems (Mohapatra, 2025).

Precision management of water, nutrients, and feed leverages sensor networks and decision-support systems to optimize input use in an efficient and sustainable manner. Sensor-based irrigation systems, informed by real-time soil moisture and weather data, enable targeted water application that reduces losses while maintaining optimal crop and pasture conditions (Soussi et al., 2024; Alahmad et al., 2023). Similarly, precision nutrient management relies on spatially explicit soil and crop data to guide variable-rate fertilization, reducing over-application, lowering production costs, and mitigating nutrient runoff that contributes to environmental pollution (Alahmad et al., 2023; Ronzhin et al., 2025). In livestock operations, precision feeding systems integrate sensor-derived data and individual animal information to adjust rations according to growth stage, health status, and environmental conditions, improving feed efficiency and reducing emissions intensity per unit of product.

A central pillar of digital transformation is the use of big data analytics and advanced modeling to optimize productivity, reduce emissions, and improve resource planning across integrated agricultural systems. Data generated from IoT networks, UAV and satellite imagery, and farm management records feed into predictive models, machine learning algorithms, and decision-support tools that can forecast yields, identify risk zones, and recommend optimized management strategies (Alahmad et al., 2023; Ronzhin et al., 2025). These analytical approaches enable the interpretation of complex datasets, uncovering patterns and trends that inform long-term strategic planning and support climate adaptation, resource efficiency, and environmental sustainability (Padhiary et al., 2025).

Digital transformation and precision management integrate IoT sensors, GIS, unmanned aerial vehicles, and data analytics to create responsive, efficient, and sustainable agricultural systems. These technologies enhance monitoring of crops and livestock, optimize input use, support informed decision-making, and improve the capacity of integrated systems to adapt to climatic and resource constraints.

ENVIRONMENTAL SUSTAINABILITY AND CLIMATE ADAPTATION

Environmental sustainability and climate adaptation are central components of integrated agroforestry and livestock systems. These systems provide multiple ecosystem services that

contribute to soil and water conservation, biodiversity enhancement, carbon sequestration, and resilience to climatic variability. Their multifunctionality positions agroforestry-livestock systems as important land-use strategies for sustainable agribusiness under global environmental change (FAO, 2011; Jamnadass et al., 2013).

Agroforestry and integrated livestock systems contribute substantially to soil, water, and biodiversity conservation by modifying biophysical processes and landscape structure. Trees and shrubs integrated within agricultural landscapes reduce soil erosion by limiting surface runoff and stabilizing soil through extensive root systems, thereby improving soil structure and aggregate stability compared with monoculture cropping systems (FAO, 2011; Mosquera-Losada et al., 2005). Increased organic matter inputs from litterfall, root turnover, and woody biomass enhance soil fertility and water-holding capacity, improving resilience to drought and intense rainfall events (Jamnadass et al., 2013; García de Jalón et al., 2018). Agroforestry systems also diversify habitat structures, supporting higher levels of plant and animal biodiversity than simplified agricultural landscapes, which in turn promotes ecosystem stability and functional services such as pollination and biological regulation (Paudel et al., 2025; Tirkey et al., 2024).

A key environmental function of agroforestry systems is carbon sequestration and their contribution to climate change mitigation. The integration of woody perennials with crops and livestock increases above- and below-ground biomass carbon stocks and promotes the accumulation of soil organic carbon through litter deposition and root-derived inputs (FAO, 2011; Hess, 2025). In silvopastoral systems, tree cover enhances carbon storage in vegetation and soil while moderating microclimatic conditions such as shading and wind exposure, contributing to improved ecosystem carbon balance and resilience to climatic extremes (Mosquera-Losada et al., 2005; Hess, 2025).

Beyond mitigation, agroforestry systems support climate adaptation through structural designs that moderate climatic extremes and improve resource-use efficiency. Multilayered configurations, including silvopastoral arrangements and tree-based buffer systems, regulate microclimates, reduce temperature variability, and conserve soil moisture (García de Jalón et al., 2018). Improved soil porosity and organic matter content enhance water infiltration and retention, increasing system resilience to both drought and flood conditions (FAO, 2011; New Climate Institute, 2020). In grazing systems, the integration of livestock with tree cover moderates pasture microclimates, reduces animal heat stress, and supports forage productivity under variable climatic conditions (Mosquera-Losada et al., 2005).

Collectively, the environmental services provided by agroforestry and integrated livestock systems, including soil protection, water conservation, biodiversity enhancement, carbon sequestration, and climate adaptation, offer holistic pathways for sustainable agribusiness transformation. Scaling up these systems requires supportive policy frameworks, knowledge transfer, and capacity building to enable the widespread adoption of practices that enhance ecosystem services while maintaining farm productivity and resilience.

ECONOMIC AND SOCIAL DIMENSIONS OF AGROFORESTRY AND INTEGRATED LIVESTOCK SYSTEMS

Economic and social dimensions are fundamental for understanding the viability and broader societal impacts of integrated agroforestry and livestock systems. Beyond

ecological benefits, these systems contribute to economic sustainability through income diversification and risk reduction, strengthen rural livelihoods and employment, and require supportive institutional and policy frameworks to enable wider adoption.

Integrated agroforestry and livestock systems enhance economic sustainability by generating diverse income streams that reduce farmers' dependence on single crops or products. The combined production of food crops, fodder, tree products, and livestock outputs provides multiple revenue sources that buffer households against market volatility and climate-related production risks, thereby improving economic resilience (Paudel et al., 2025; Tirkey et al., 2024). Diversified systems also create opportunities for value addition through processing and local marketing of agricultural and tree-based products, contributing to rural economic development (Jamnadass et al., 2013).

Economic resilience is further strengthened by the reduced likelihood of complete yield failure in diversified systems. Agroforestry can function as a livelihood safety net by providing alternative income sources during periods of climatic stress, such as droughts or floods, thereby supporting long-term financial stability. In addition, integrated systems often reduce reliance on external inputs, including synthetic fertilizers and pesticides, which lowers production costs and improves net farm returns, particularly in resource-limited farming contexts (Bhandari et al., 2025).

The social implications of integrated agroforestry and livestock systems extend beyond income generation. Agroforestry contributes to improved rural livelihoods by supporting food and feed availability, fuel resources, and overall household security, particularly in vulnerable and smallholder communities (Jamnadass et al., 2013; World Agroforestry Centre and FAO, 2013). These systems also generate employment across diversified value chains, including nursery production, on-farm management, and product processing, thereby supporting local economies and reducing pressures for rural-to-urban migration (Tirkey et al., 2024).

Beyond their economic role, agroforestry systems foster social cohesion and knowledge exchange within rural communities. Collective activities related to tree management, grazing coordination, and product marketing strengthen social networks and facilitate the sharing of traditional and technical knowledge. Such interactions contribute to human capital development, enhance collective decision-making, and support resilient community structures (Bhandari et al., 2025).

The successful adoption and scaling of integrated agroforestry and livestock systems depend on enabling policies, institutional support, and appropriate economic incentives. Policy frameworks that recognize multifunctional land use, secure land tenure, and support investments in sustainable practices are critical for long-term implementation. Financial mechanisms, including incentives for ecosystem service provision and access to credit, can further encourage adoption by recognizing the broader social and environmental benefits of integrated systems (FAO, 2011; New Climate Institute, 2020; Bashiru and Oseni, 2025).

In summary, the economic and social dimensions of integrated agroforestry and livestock systems highlight the importance of income diversification, improved rural livelihoods, employment generation, and supportive policy environments as key drivers of long-term

economic stability and community well-being. Integrating these dimensions into research, policy design, and extension services will be essential to expand adoption and fully realize the potential of agroforestry-based systems for sustainable agribusiness development.

AGROFORESTRY AND INTEGRATED LIVESTOCK SYSTEMS FOR NUTRITION SECURITY AND CIRCULAR BIO-ECONOMY

Integrated agroforestry and livestock systems contribute to improved nutritional outcomes, sustainable animal production, and public health, while also providing pathways toward a circular bio-economy through renewable energy generation and nutrient recycling. By integrating trees, crops, and livestock, these systems exploit ecological synergies that enhance the diversity and quality of food products, reduce environmental footprints, and valorize biomass and organic residues.

Agroforestry systems directly support dietary diversification and improved nutritional security by producing a wide range of food products, including fruits, vegetables, nuts, grains, milk, and meat, often within the same land unit. The inclusion of trees and perennial species increases the availability of micronutrient-rich foods and expands dietary diversity beyond monocultural staples, which has been linked to improved nutritional outcomes at household and community levels (Jamnadass et al., 2013; World Agroforestry Centre and FAO, 2013).

The integration of livestock within agroforestry contexts further enhances food quality through the provision of animal-sourced foods that supply high-quality proteins, essential fatty acids, and key micronutrients critical for human health (Varijakshapanicker et al., 2019). In silvopastoral systems, diversified forage resources derived from tree-pasture interactions improve feed quality and animal nutrition, supporting animal welfare and productivity and contributing to improved milk and meat quality compared with simplified grazing systems (Mosquera-Losada et al., 2005).

By broadening the feed base and incorporating tree-derived fodder resources, integrated systems reduce dependence on external feed inputs while improving nutrient utilization efficiency. Such diversification enhances the stability of animal performance under climatic variability and supports locally available, nutrition-sensitive food production systems that strengthen food security and public health outcomes (Jamnadass et al., 2013; Paudel et al., 2025).

Integrated agroforestry and livestock systems also play a significant role in advancing circular bio-economy principles by converting agricultural and livestock biomass into renewable energy and recyclable nutrients. Anaerobic digestion of manure and crop residues represents a key pathway for transforming organic waste into biogas while producing nutrient-rich digestate that can be returned to soils as fertilizer, thereby closing nutrient cycles and reducing reliance on external inputs (Pan et al., 2021). Such systems mitigate greenhouse gas emissions through methane capture, enhance rural energy security, and generate additional income streams for farm households (Pan et al., 2021; Manono and Gichana, 2025).

Together, agroforestry and integrated livestock systems support nutrition-sensitive food production by delivering diverse, high-quality plant and animal products while linking agricultural productivity with public health benefits. At the same time, the integration of bioenergy generation and nutrient recycling embeds these systems within circular bio-economy frameworks, reducing environmental impacts and strengthening economic resilience. These multifunctional pathways underscore the potential of integrated agroecosystems to contribute to sustainable agribusiness development, food security, and climate-responsive rural transformation.

CONCLUSION

Integrated agroforestry and livestock systems offer a multifunctional approach to climate-resilient agribusiness by simultaneously enhancing ecological, economic, and social outcomes. These systems improve soil and water conservation, support biodiversity, and increase carbon sequestration, while providing high-quality plant and animal products that enhance nutritional security. The integration of technological innovations and precision management optimizes resource use, reduces environmental impact, and strengthens farm-level resilience. Additionally, circular bio-economy practices, including biomass and waste valorization, contribute to renewable energy production and nutrient recycling. Socially, these systems support rural livelihoods, employment, and knowledge transfer, reinforcing community stability. Overall, agroforestry-livestock integration represents a holistic and scalable strategy for sustainable, productive, and climate-adaptive agribusiness.

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DETERMINATION OF THE EFFECTS OF SAFFLOWER BIODIESEL BLEND RATIOS ON THE PERFORMANCE AND EMISSIONS OF A SINGLE-CYLINDER INDUSTRIAL DIESEL ENGINE

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Abstract: The gradual depletion of fossil fuel reserves, combined with increasing economic constraints and growing environmental concerns, has substantially intensified the demand for alternative energy sources. Biodiesel produced from vegetable oils has emerged as a prominent renewable fuel due to its sustainable nature, low environmental impact, and high compatibility with conventional compression ignition engines. In this context, safflower oil provides significant techno-economic advantages owing to its high unsaturated fatty acid content, low viscosity, and broad agronomic adaptability. This study experimentally investigates the effects of blending safflower seed oil with conventional diesel fuel at volumetric ratios of 5 and 15% on the performance and exhaust emission characteristics of a single-cylinder diesel engine. The results indicate that the 5% safflower diesel blend maintains engine power output comparable to that of pure diesel across all load conditions, whereas the 15% blend leads to a slight reduction in brake power. Emission measurements reveal a minor decrease in carbon monoxide (CO) concentrations for both blend ratios, while nitrogen oxide (NO_x) emissions increase due to altered combustion behavior and elevated in-cylinder temperatures. Load-dependent performance analysis shows that the brake-specific fuel consumption remains nearly unchanged for the 5% blend, whereas the 15% blend results in a moderate increase. Overall, the findings suggest that blending 5% safflower seed oil with conventional diesel achieves an optimal balance between engine performance and emission characteristics, representing a technically advantageous option for diesel engine operation.

Keywords: Energy, Diesel engine, Safflower oil biodiesel, Exhaust emissions

INTRODUCTION

Rapid advancements in technology and the increasing global focus on environmental sustainability have made profound changes in the energy sector unavoidable. The limited availability of conventional energy resources, along with the escalating environmental consequences of their use, necessitates a shift toward more sustainable energy production and consumption strategies (Doğan et al., 2024). Reflecting this trend, the automotive industry has placed greater emphasis on alternative fuels aimed at reducing dependency on traditional petroleum-based fuels. Among these, innovative diesel blends incorporating various additives are considered promising solutions to address future energy demands. Despite these efforts, fossil fuels continue to dominate global energy consumption (Kesharvani et al., 2023).

Diesel engines, in particular, are widely employed in commercial transport, agriculture, and industrial sectors due to their high fuel efficiency, reliability, and long operational life. However, the environmental impact of petroleum-derived diesel and the ongoing depletion of fossil fuel reserves have prompted intensified research into sustainable and eco-friendly alternatives (Krishnamoorthi et al., 2024). Biodiesel has emerged as a notable candidate in this regard, offering renewable production routes and a comparatively lower environmental footprint (Rajak et al., 2023). It can be synthesized from diverse organic feedstocks, including vegetable oils, animal fats, microalgal oils, and waste oils. Extensive research has investigated biodiesel utilization in diesel engines, focusing on how different blend ratios affect engine performance and emissions. Findings indicate that pure biodiesel (100%) can be used without major engine modifications, highlighting its potential as a large-scale sustainable energy source (Chen et al., 2024). Additionally, biodiesel has been shown to reduce exhaust emissions, supporting its role as an environmentally compatible alternative for conventional diesel engines.

Diesel-powered internal combustion engines also play a critical role in construction and auxiliary machinery used in road and bridge projects. While their widespread adoption boosts productivity and economic growth, it simultaneously underscores the need for more efficient and cleaner technologies (Zheng et al., 2008; Kanimozhi et al., 2022). Experimental studies on safflower oil biodiesel, enhanced with CeO₂ nanoparticles and hydrogen, have demonstrated improvements in engine power, torque, and thermal efficiency, along with reductions in CO and CO₂ emissions. Minor increases in NO_x were observed, suggesting a need for careful optimization (Wang et al., 2023). Biodiesel production parameters, such as methanol-to-oil ratio, catalyst concentration, reaction temperature and time, and stirring speed, critically affect yield. Optimal conditions for safflower oil biodiesel have been reported as a 16:1 molar ratio, 4 g KOH catalyst, 60 °C reaction temperature, 4 hour reaction time, and 700 rpm stirring, achieving approximately 90% yield. Subsequent blends, including B20, B30, and B40, showed that the B20 blend achieved brake thermal efficiency comparable to conventional diesel while significantly reducing CO, HC, and smoke emissions. However, NO_x emissions were slightly elevated due to the higher cetane number of neat biodiesel (Asokan et al., 2021). High viscosity remains a challenge for biodiesel, influencing combustion, performance, and emissions.

Studies on injection timing in safflower methyl ester (SAME)-fueled diesel engines revealed that retarded injection reduced NO_x, CO, and smoke emissions but slightly lowered brake thermal efficiency, while advanced timing increased NO_x emissions with marginal smoke reduction. These results underscore that careful injection timing can optimize the trade-off between performance and emissions, confirming the practical potential of safflower methyl ester as an alternative fuel for transportation applications (Rajendran et al., 2023).

In contrast to the existing literature, the present study systematically investigates the effects of varying blend ratios of safflower seed oil-based biodiesel on diesel engine performance and exhaust emissions. By identifying optimal blending ratios, this work provides valuable insights that contribute to both improved engine efficiency and enhanced environmental sustainability.

MATERIAL AND METHODS

In this study, commercial diesel fuel and biodiesel blends derived from safflower seed oil were used as test fuels. Safflower seed oil was blended with diesel fuel on a volumetric basis. Within the scope of the experimental investigations, two different blends were prepared: 5% safflower seed oil 95% diesel (B5) and 15% safflower seed oil 85% diesel (B15). The homogeneity of the blends was ensured using a mechanical stirrer at ambient temperature, and no phase separation or sedimentation was observed during the experiments. Neat diesel fuel was used as the reference fuel for comparison purposes. The experiments were conducted on a single-cylinder, four-stroke, direct-injection diesel engine, as shown in Figure 1. No modifications were made to the engine, allowing the direct assessment of the effects of safflower seed oil-based biodiesel blends on engine performance.

Engine load was gradually increased using a dynamometer, and measurements were recorded once steady-state operating conditions were achieved at each load level. For each fuel type, tests were carried out at engine load levels of 25, 50, 75 and 100%, and the corresponding engine performance parameters and exhaust emissions were recorded. All tests were performed after the engine reached its normal operating temperature, with baseline measurements first obtained using neat diesel fuel. The same experimental procedure was subsequently repeated for the B5 and B15 blends. To ensure data consistency and repeatability, all measurements were conducted under constant ambient conditions. Engine performance was evaluated in terms of brake power, brake specific fuel consumption (BSFC), and load-dependent variations in power output. Fuel consumption was determined by measuring the amount of fuel consumed over a specified time interval. Using the measured data, the performance parameters for each fuel were calculated and compared with those of neat diesel fuel. Performance and emission results were analyzed as a function of engine load, enabling a systematic evaluation of the influence of safflower seed oil content on engine behavior.



Figure 1. Experimental setup of the diesel engine used for performance testing

Table 1. Technical specifications of the diesel engine used in the experimental investigation

General Characteristics	Technical Specification
Engine type	Erin motor base model
Number of valves	4
Continuous power (kw/rpm)	11.5/1500
Bore (mm)	108
Stroke (mm)	127
Combustion system	Direct injection
Compression ratio	14.6 : 1
Engine cooling	Water
Weight (kg)	157

RESULTS AND DISCUSSION

The experimental results obtained in this study comprehensively demonstrate the effects of incorporating safflower seed oil into diesel fuel at blend ratios of 5% safflower seed oil 95% diesel (B5) and 15% safflower seed oil 85% diesel (B15) on engine performance and exhaust emission characteristics. An examination of the power output data derived from the engine tests indicates that the use of both biodiesel blends at various engine load conditions yields power values that are very close to those obtained with neat diesel fuel. This finding strongly supports the feasibility of the proposed biodiesel blends as alternative engine fuels and confirms that they do not impose a significant adverse effect on engine power output. Furthermore, the comparable performance of the B5 and B15 blends to that of diesel fuel under low and medium load conditions suggests that the addition of safflower seed oil does not markedly deteriorate engine operating efficiency. These results indicate that the engine can operate reliably with these blends across a wide range of loading conditions, highlighting the practical applicability of safflower seed oil-based biodiesel blends without compromising engine performance.

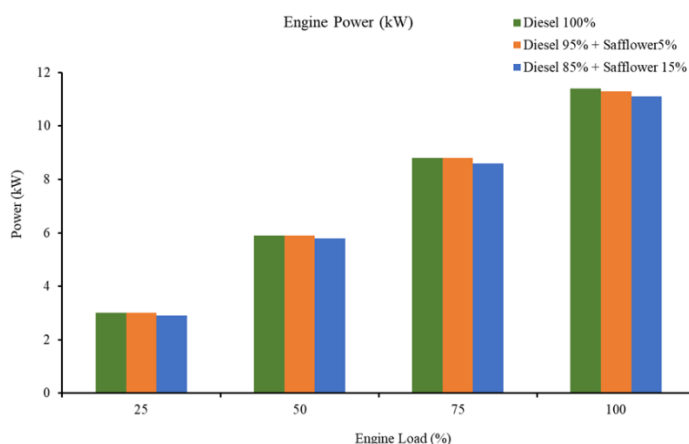


Figure 2. Comparative analysis of engine power output for different biodiesel-diesel blends

As illustrated in Figure 2, a comparison of the power outputs measured at 25, 50 and 75% engine load conditions using conventional diesel fuel and those obtained with 5% safflower seed oil-based biodiesel (B5) reveals that the engine power values are largely comparable

for both fuels. Only at full load (100%) did the B5 blend exhibit a very slight reduction in engine power of approximately 0.1 kW, indicating a negligible impact on overall performance. In contrast, when the engine was fueled with 15% safflower seed oil-based biodiesel (B15), a power reduction of about 0.2 kW was observed at 25, 50, and 75% load conditions. At 100% engine load, the decrease in power reached approximately 0.3 kW. These results suggest that although the reduction in engine performance remains limited, it becomes more noticeable with increasing biodiesel blending ratio. As also evident in Figure 2, the addition of 5% safflower seed oil to conventional diesel fuel does not result in a significant change in engine power, and the power output is largely preserved when compared with neat diesel operation.

According to the data presented in Figure 3, when the engine was fueled with 5% safflower seed oil-based biodiesel (B5), the fuel consumption values at all applied load conditions were found to be largely comparable to those obtained with conventional diesel fuel. This observation indicates that a low biodiesel blending ratio does not adversely affect the fuel efficiency of the engine. In contrast, the use of 15% safflower seed oil-based biodiesel (B15) resulted in an increase in fuel consumption depending on the engine load. The measurements revealed an increase in consumption ranging approximately from 14 mL/h to 108 mL/h.

These findings suggest that a low biodiesel blending ratio (5%) is more favorable in terms of fuel consumption, providing a more balanced trade-off between engine performance and fuel efficiency. The observed differences can primarily be attributed to the lower energy content, particularly the lower heating value, of biodiesel compared with conventional diesel fuel. In addition, the distinct physical and chemical properties of biodiesel are expected to influence in-cylinder combustion processes, air fuel mixing, and injection characteristics, thereby leading to variations in fuel consumption. Within this context, it can be concluded that low-percentage biodiesel blends can be applied without compromising engine performance and fuel efficiency, whereas higher blending ratios may lead to increased fuel consumption.

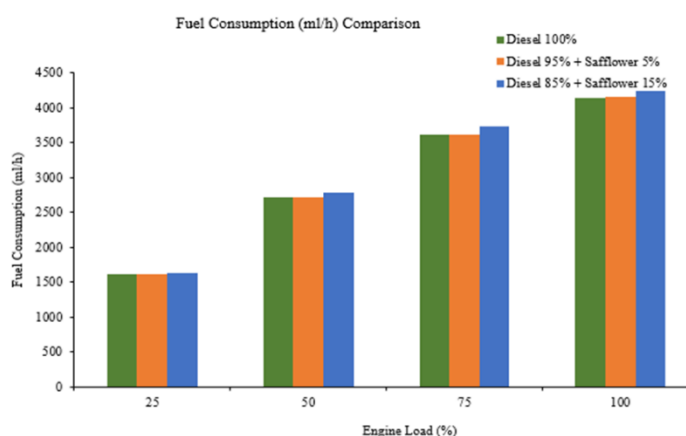


Figure 3. Comparative assessment of engine fuel consumption for various biodiesel-diesel blends

Based on the data presented in Figure 4, the influence of safflower seed oil-based biodiesel blends on carbon monoxide (CO) emissions in the exhaust gases was evaluated, and a pronounced reduction in CO emissions was observed at all engine load conditions. In

particular, the addition of 15% safflower seed oil biodiesel (B15) to conventional diesel fuel led to a substantial decrease in CO emissions, indicating that biodiesel promotes cleaner combustion processes within the engine. However, when the effects on engine power and fuel consumption are considered simultaneously, the lower safflower seed oil blending ratio (5%, B5) emerges as a more balanced option in terms of overall engine performance and fuel efficiency. In other words, although both blends demonstrate a clear potential for reducing CO emissions, the B5 blend provides a more favorable operational profile when emission reduction is evaluated together with performance and consumption parameters.

In conclusion, the use of safflower seed oil-based biodiesel can be regarded as a viable alternative fuel for diesel engines, contributing to environmental sustainability through the reduction of carbon monoxide emissions.

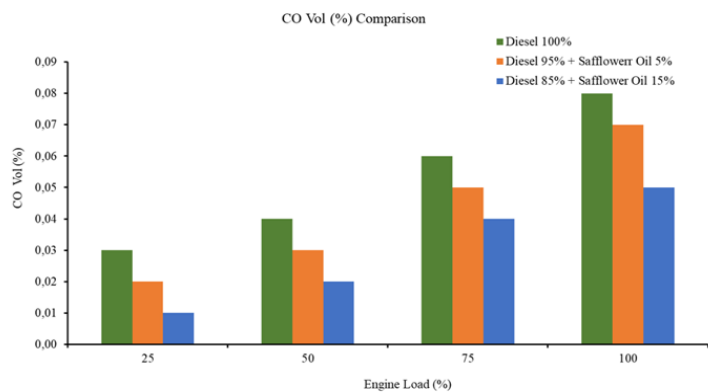


Figure 4. Comparative evaluation of carbon monoxide (CO) emissions for different biodiesel-diesel blends

These findings further support the view that biodiesel is not only a renewable energy source but also an environmentally friendly fuel option capable of mitigating exhaust emissions. According to the data presented in Figure 5, the use of biodiesel-blended fuels resulted in a limited increase in nitrogen oxides (NO_x) emissions at all engine load conditions. These increases ranged approximately between 52 and 145 ppm across different loads, and the overall emission levels were found to remain within acceptable limits.

The primary reason for the observed rise in NO_x emissions is attributed to the higher in-cylinder temperatures attained during the combustion of biodiesel compared with conventional diesel fuel, which inherently promotes NO_x formation. The more pronounced increase in NO_x emissions at higher engine loads emerges as a critical parameter that must be carefully considered when evaluating the environmental performance of biodiesel fuels. This finding suggests that the widespread application of biodiesel in diesel engines may require additional technical measures or emission mitigation strategies to effectively control NO_x emissions. In this context, the integration of appropriate combustion optimization techniques and emission control technologies is essential to enhance the environmental sustainability of biodiesel fuels while maintaining satisfactory engine performance.

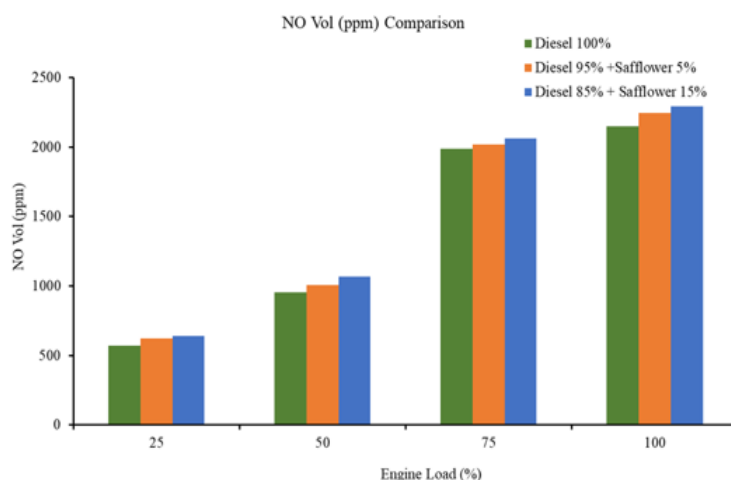


Figure 5. Comparative evaluation of nitrogen oxide (NO_x) emissions for different biodiesel-diesel blends

CONCLUSION

This study systematically evaluated the effects of safflower seed oil-based biodiesel additions (5 and 15%) on the performance and exhaust emissions of a single-cylinder diesel engine. The results showed that the 5% biodiesel blend (B5) produced engine power values nearly identical to those of neat diesel fuel at 25, 50, and 75% load conditions, with only a negligible reduction of 0.1 kW observed at full load. In contrast, the 15% biodiesel blend (B15) led to a limited but noticeable decrease in engine power as the load increased, reaching a maximum reduction of 0.3 kW at 100% load, indicating that higher biodiesel blending ratios may slightly affect engine performance.

Fuel consumption measurements revealed that the B5 blend achieved consumption levels comparable to conventional diesel across all load conditions. However, the B15 blend resulted in an increase in fuel consumption ranging from 14 to 108 mL/h depending on engine load, primarily due to the lower heating value and distinct physicochemical properties of biodiesel. Emission analyses demonstrated that biodiesel blending significantly reduced carbon monoxide (CO) emissions at all loads, with the B15 blend providing the greatest reduction. Nevertheless, when performance and fuel consumption were considered together, the B5 blend offered a more balanced operating profile. A moderate increase in nitrogen oxides (NO_x) emissions (52–145 ppm) was observed, particularly at higher loads, which can be attributed to the higher in-cylinder temperatures associated with biodiesel combustion. This finding highlights the need for appropriate emission control or combustion optimization strategies to mitigate NO_x emissions.

Overall, the results indicate that low-percentage (5%) safflower seed oil-based biodiesel can be utilized without compromising engine performance or fuel efficiency, while effectively reducing CO emissions and enhancing environmental sustainability. Although higher biodiesel content (15%) slightly affects power and fuel consumption, it still offers notable emission benefits. These findings support the technical feasibility and environmental potential of safflower seed oil-based biodiesel as a sustainable and eco-friendly alternative fuel for diesel engines.

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CLIMATE CHANGE RISKS AND CHALLENGES IN GLOBAL AGRICULTURE

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Abstract: Climate change is a major global challenge, with agriculture being highly vulnerable. Rising temperatures, altered precipitation, and extreme weather events threaten crop yields, livestock productivity, and food security. These changes increase risks such as heat stress, droughts, floods, and pest outbreaks. This study analyzes the impacts of climate change on agriculture and highlights adaptive strategies to enhance resilience and sustainability.

Keywords: Climate change, Agriculture, Crop production, Livestock, Food security, Sustainability

INTRODUCTION

Climate change represents one of the most significant challenges facing contemporary society, with profound implications for both natural and socio-economic systems worldwide. According to the Intergovernmental Panel on Climate Change (IPCC), the primary driver of recent climate change is the increase in greenhouse gas concentrations resulting from human activities, particularly the combustion of fossil fuels, land-use change, and intensified industrial and agricultural production (IPCC, 2021). Global mean surface temperature has already risen by approximately 1.1°C above pre-industrial levels, substantially increasing the likelihood of irreversible changes within the climate system.

A defining characteristic of climate change is the clear trend of rising global temperatures, accompanied by alterations in precipitation patterns and an increasing frequency and intensity of extreme weather events. Observational data and climate projections indicate more frequent and severe heatwaves, prolonged droughts, intense rainfall events, floods, and storms across many regions of the world (IPCC, 2022). These climatic changes do not occur uniformly; instead, their magnitude and impacts vary spatially, with certain regions and vulnerable sectors experiencing disproportionately severe effects.

The impacts of climate change extend beyond physical environmental changes, significantly affecting ecosystem functioning and socio-economic stability. Climate-induced stresses contribute to ecosystem degradation, biodiversity loss, and the disruption of essential ecosystem services, including climate regulation, water availability, and soil

fertility (Millennium Ecosystem Assessment, 2005; IPBES, 2019). At the same time, climate change poses substantial risks to human well-being by affecting food security, water resources, public health, livelihoods, and economic development. The Food and Agriculture Organization of the United Nations (FAO) emphasizes that climate change exacerbates existing socio-economic inequalities and represents a major obstacle to achieving sustainable development, particularly in rural areas and agriculture-dependent communities (FAO, 2018).

In this global context, understanding the interconnections between climate dynamics and their impacts on natural and socio-economic systems is essential for developing effective mitigation and adaptation strategies. Such understanding forms the foundation for enhancing resilience and sustainability in key sectors, including agriculture, which is among the most climate-sensitive components of the global economy.

MATERIAL AND METHODS

This study employed a literature-based analytical approach to assess the impacts of climate change on agricultural systems and food security, as well as adaptation strategies across different regions. Peer-reviewed articles, reports from the IPCC, FAO, and other international and regional sources were reviewed to examine temperature and precipitation changes, extreme weather events, crop and livestock productivity, pest and disease dynamics, and socio-economic consequences for food availability, access, utilization, and stability. Adaptation measures were analyzed across field-level practices, livestock management, integration of traditional knowledge with technical innovations, and institutional support mechanisms.

RESULTS AND DISCUSSION

Impacts of Climate Change on Agricultural Systems

The analysis indicates that climate change exerts significant and multidimensional impacts on agricultural systems worldwide. Rising average temperatures have been consistently associated with reduced crop yields, particularly for temperature-sensitive crops such as wheat, maize, and rice, especially in tropical and subtropical regions (IPCC, 2022). Heat stress negatively affects plant physiological processes, including photosynthesis and grain filling, while also reducing livestock productivity through decreased feed intake, fertility, and increased mortality rates (Rojas-Downing et al., 2017).

These climate-driven changes in agricultural systems directly translate into broader challenges for food security. Reduced crop yields, livestock productivity losses, and disruptions in cropping patterns compromise the availability and accessibility of food, while increased vulnerability of farming communities threatens both the stability and utilization of food supplies. Understanding these pathways is essential to link the biophysical impacts of climate change with the four interrelated dimensions of food security

Impacts From Climate Change Drivers on the Four Dimensions of Food Security

Climate change affects food security through multiple, interconnected mechanisms that influence the four core dimensions of food security: availability, access, utilisation, and

stability. These mechanisms operate through changes in temperature, precipitation patterns, and the frequency and intensity of extreme weather events, with uneven impacts across regions, production systems, and socio-economic groups (FAO, 2018; IPCC, 2022).

Impacts on Food Availability

Climate-induced increases in temperature and the frequency of drought events reduce crop and livestock productivity by intensifying heat stress, degrading soil fertility, and accelerating land degradation. These impacts are particularly severe in countries where a large share of the population depends on agriculture for livelihoods and where food production systems rely heavily on rainfed agriculture and pastoral rangelands (FAO, 2018; Mbow et al., 2019). Reduced yields in these systems directly constrain food availability and increase vulnerability among both rural and urban poor populations. Extreme heat events further affect agricultural production by reducing crop productivity and, when combined with high humidity, significantly lowering agricultural labour capacity and animal performance. Countries and sectors dependent on outdoor manual agricultural labour in hot and humid climates are especially vulnerable to these impacts, as heat stress limits both working hours and labour efficiency (FAO, 2018).

Rising temperatures and changes in precipitation regimes also contribute to the expansion and geographic redistribution of crop and livestock pests and diseases. For example, pastoral communities in East Africa have experienced increased livestock morbidity and mortality due to Rift Valley fever outbreaks during El Niño years, highlighting the link between climate variability and animal health risks (Bebber, 2015; FAO, 2018).

In addition, higher temperatures and drought stress have increased post-harvest losses, particularly through the proliferation of mycotoxins in food and feed. These risks are most pronounced in tropical and subtropical regions where food safety surveillance and storage infrastructure are limited, further undermining food availability and quality (FAO, 2018).

Impacts on Food Access

Climate change affects food access primarily through its impacts on agricultural incomes, food prices, and food distribution systems. Increased droughts, floods, and pest outbreaks reduce agricultural yields and raise production costs, including those associated with water and pest management. As a result, smallholder farmers and pastoralists in low-income regions experience declining incomes and reduced ability to purchase sufficient and diverse foods (Saronga et al., 2016; FAO, 2018; Mbow et al., 2019).

The growing number and intensity of extreme weather events have also been linked to rising food prices and increased price volatility. Higher food prices disproportionately affect low-income consumers, particularly women and girls, often leading to reduced dietary diversity and lower overall food consumption (FAO, 2018; Ilboudo Nebie et al., 2021).

Extreme events such as floods disrupt food storage facilities, transportation networks, and market access, further constraining both physical and economic access to food. These impacts are especially severe in countries dependent on food imports, including Small

Island Developing States, as well as among poor households in flood-prone and saline regions, such as monocropped rice-growing areas in Bangladesh. (FAO, 2018; Algur et al., 2021).

Impacts on Food Utilisation (Food Quality and Safety)

Food utilisation is increasingly affected by climate change through impacts on food safety, nutritional quality, and dietary diversity. Rising temperatures promote the growth of microorganisms and increase contamination risks, including higher levels of mycotoxins in food and feed, particularly in countries with limited food safety monitoring and regulatory capacity (FAO, 2018; Mbow et al., 2019). Climate extremes also influence food affordability and consumption patterns. Fruits and vegetables often become relatively more expensive following climate shocks, making them less accessible compared to calorie-dense but nutrient-poor foods. Urban low-income households and rural households that rely primarily on food purchases are particularly affected, while children in regions such as West Africa face increased risks of reduced dietary diversity and undernutrition due to climate-driven food shortages (Niles et al., 2021).

Impacts on Food Stability

Climate change undermines food system stability by increasing variability in production, incomes, and food supply over time. The rising frequency and severity of droughts and heatwaves lead to recurrent production losses and disruptions to food transport systems, contributing to unstable food supplies, particularly in landlocked and low-income countries reliant on food imports (FAO, 2018; Algur et al., 2021).

Small-scale producers and fishers are especially vulnerable to climate-induced income instability, as droughts, floods, and rising temperatures increase the incidence of pests and diseases and reduce the reliability of agricultural and fisheries-based livelihoods (FAO, 2018). In some temperate regions, reduced frost and snow days may increase food stability by lengthening growing seasons and reducing frost-related crop losses. However, these potential benefits are often offset by heightened risks of pest and pathogen expansion, limiting long-term gains in food security (Ranasinghe et al., 2021).

Adaptive Strategies to Enhance Resilience and Sustainability: Climate Change Adaptation Strategies

Adaptation is widely recognized as the most effective strategy to minimize negative impacts on crop and livestock productivity and to maintain food security (Kamali et al., 2025). Agricultural adaptation involves deliberate actions to anticipate climate risks and modify farming practices, resource management, and infrastructure. The primary aim of adaptation is to increase societal and community resilience to climate-induced shocks (Ricart et al., 2019). Farmers adopt diverse strategies at the field level, including modifying crop areas, changing cropping patterns, adopting drought- or heat-tolerant varieties, adjusting planting calendars, and diversifying crop portfolios (Matewos, 2020). Water management is particularly critical for adaptation. Practices such as deepening wells, enhancing irrigation systems, storing water on-farm, and adopting micro-irrigation techniques help mitigate drought impacts and optimize water use (Srivastav et al., 2021).

In water-stressed regions, farmers often combine traditional knowledge with improved irrigation methods to cope with prolonged dry periods.

Livestock systems are also adapting to climate variability through strategies such as reducing herd sizes, modifying feed composition, providing supplementary feeding, and adjusting grazing schedules (Karimi et al., 2018). These absorptive measures allow farmers to buffer short-term climate shocks while maintaining production stability. Traditional agricultural practices, such as agroforestry, intercropping, crop rotation, cover cropping, organic composting, and integrated crop-livestock systems, remain foundational for adaptation. These approaches form part of Climate-Smart Agriculture (CSA), which combines productivity, adaptation, and mitigation objectives into a single framework (Singh and Singh, 2017). Integration of local knowledge with modern scientific tools enhances adaptive capacity. Indigenous knowledge provides critical insights into climate patterns and resource management, while technical tools, including climate forecasts and decision-support systems, assist farmers in making informed management decisions. In water-scarce areas, households often adopt agronomic adjustments such as reduced cultivation area, shortened irrigation furrows, and optimized fertilizer use to cope with water limitations (Srivastav et al., 2021).

Extension services, among others, influence adaptive capacity and thus play a pivotal role in educating farmers, disseminating climate information, promoting adaptive technologies, and connecting farmers to markets and input suppliers. Incorporating farmers' experiences into policy design enhances the effectiveness of adaptation strategies and reduces vulnerability to climate risks (Acevedo et al., 2020).

Adaptive Strategies for European Agriculture Under Climate Change

Europe is experiencing diverse impacts of climate change on agricultural systems, including rising temperatures, more frequent extreme weather events, altered precipitation patterns, and shifts in seasonal cycles (Hatfield et al., 2020). These changes have already led to yield losses, reduced cultivable area, and declining soil organic matter in several regions (FAO, 2018).

In northern Europe, Finland faces warmer, wetter winters and drier, hotter summers, with more frequent extreme events such as storms and heatwaves. These conditions have extended growing seasons and reduced snow cover but increased the risk of soil degradation (Himanen et al., 2016). Farmers have adopted intercropping systems, under-sowing cereals with perennial grasses, and using diverse forage mixtures to improve soil fertility and quality (Himanen et al., 2016). Similarly, in Scotland, projections indicate hotter, drier summers and wetter winters by 2100, challenging current crop growth while favouring new crop types. Adaptation strategies include rescheduling planting and harvesting, adopting climate-resilient crops, improving soil and pasture management, promoting farmer knowledge-sharing, establishing early warning systems, and optimizing fertiliser use (Jenkins et al., 2023).

Central and southern Europe also face significant challenges. Across the continent, rising temperatures and more frequent droughts have decreased crop yields and productivity, particularly in southern regions. Adaptive strategies commonly implemented include

changes in crop rotations, improved irrigation management, and intensified fertiliser use, all aimed at sustaining production under increasingly stressful climatic conditions (De Leo et al., 2023). In France, farmers confront variable temperature, frost, and wind patterns, alongside more frequent heatwaves and droughts. Adaptation practices in French agriculture include cover crops, mulching, agroforestry, crop diversification, and climate-control technologies in tunnels, complemented by efficient irrigation systems (De Leo et al., 2023).

Mediterranean countries are particularly vulnerable. In Italy, recurring droughts, strong winds, floods, and pest pressures have resulted in annual crop losses of 10-40%, with extreme events causing cumulative economic damages of approximately €14 billion between 2009 and 2018. Adaptation measures encompass soil management, innovative breeding, crop protection, water management, digitization, and animal welfare improvements (De Leo et al., 2023). Greece and Cyprus face higher evapotranspiration rates and water scarcity, causing drought stress and reduced crop yields. Farmers respond with regulated irrigation, pruning, grafting, organic mulching, early sowing, intercropping with legumes, and the development of drought- and heat-tolerant crop varieties.

CONCLUSION

Climate change poses significant and multidimensional challenges to agricultural systems and food security worldwide, affecting crop and livestock productivity, pest and disease dynamics, and socio-economic conditions. The impacts are unevenly distributed, with vulnerable regions and communities facing the greatest risks, particularly those reliant on rainfed agriculture and smallholder farming. Effective adaptation requires a combination of field-level practices, traditional knowledge, technical innovations, and institutional support to enhance resilience and sustainability. Integrating these strategies can help safeguard food availability, access, utilization, and stability, ultimately supporting climate-resilient agricultural systems and sustainable development in the face of ongoing climatic changes.

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INFLUENCE OF CLIMATE CHANGE ON ENSILING

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Abstract: Climate change can affect the quantity, reliability, and quality of forage production and therefore silage preparation. In the coming decades, crops and forage plants integral to feed conservation will face rising temperatures, higher carbon dioxide levels, and highly variable water availability due to changing rainfall patterns. Contamination with undesirable microbes and chemical agents is often encountered during silage production under climate change conditions. The presence of yeasts and molds can negatively affect the nutritional value and livestock production. Future strategies in feed preparation, processing, and livestock production will focus on achieving carbon neutrality and reducing greenhouse gases in agriculture, including livestock farming, which is a global concern. Ensiling involves microbial activity followed by biochemical reactions. Changes in the silo occur almost immediately after plants are transferred from the field to the silo. The course and severity of these changes depend on various factors, mainly those that promote successful lactic acid fermentation, such as moisture content, an anaerobic environment, carbohydrate levels, and temperature.

Keywords: Silage, Livestock, Nutrition, Feed, Mycotoxins, GHG Emission

INTRODUCTION

Climate change disrupts food, water, and livelihoods by altering temperature, precipitation, and sea levels, and it affects livestock growth, milk production, reproduction, metabolism, and disease rates (Sahoo, 2018). By 2050, global food production must increase by 50% (Hamad and Tayel, 2025), despite climate change threats such as extreme weather and pests, Figure 1. Projections based on population growth and food consumption patterns indicate that by 2050, agricultural production will need to increase by at least 60-70 percent to meet demand (IPPC, 2019). The decarbonization of industrial and agricultural production, including livestock farming, has become a global trend, and many countries are aiming for carbon neutrality by 2050 (Cai, 2025). Meanwhile, total global cultivated land area has not changed since 1991 (O'Mara, 2012), reflecting increased productivity and intensification efforts (Rojas-Downing et al., 2017).

Achieving this requires optimizing land and water use through integrated approaches: enhancing soil health, employing precision agriculture, and promoting biodiversity (Wang, 2025). Climate change can influence the quantity, reliability, and quality of forage production, as well as the water needs of growing forage crops, and the patterns of large-scale rangeland vegetation (Giridhar and Samireddypalle, 2015). The most noticeable effect will be on the primary productivity of forage crops and rangelands. Developing nations are at greater risk from climate change than developed nations due to their reliance on agriculture, warmer baseline climates, and limited resources to adopt new technologies. Over the coming decades, crops and forage plants will face increasing temperatures, higher carbon dioxide levels, and highly variable water availability due to changing rainfall patterns. The combined effects of these factors will determine the actual impact on plant growth and yields. Elevated CO₂ may enhance dry matter production more in C3 plants than in C4 plants, with the response depending on crop type, soil moisture, and nutrient levels (Giridhar and Samireddypalle, 2015). Future efforts in feed preparation, processing, and livestock production will prioritize carbon-neutral research and development (Cai, 2025).

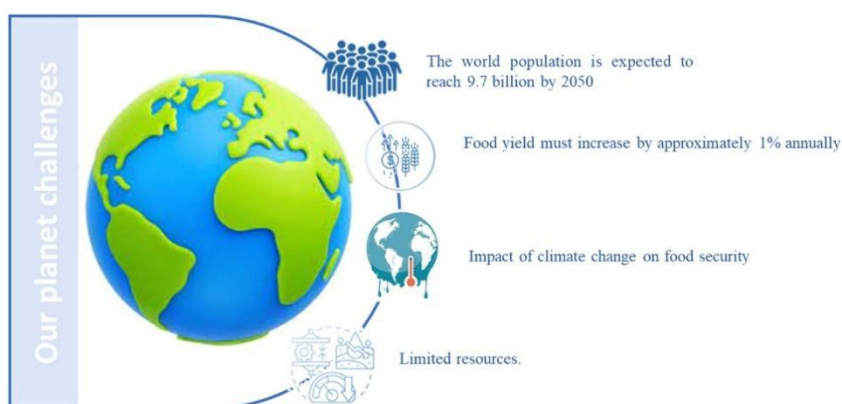


Figure 1. Challenges facing our planet by 2050 (Hamad and Tayel, 2025)

Variations in rainfall during the growing season across many regions are likely to substantially impact forage production. Since agriculture consumes the largest share of freshwater, decreasing water availability will pose a threat to forage crop yields. Nevertheless, adopting suitable adaptation strategies, backed by strong government policies, can mitigate the adverse impacts of climate change and help sustain livestock productivity by securing sufficient forage resources (Giridhar and Samireddypalle, 2015).

Silage

Ensiling is a microbial process used to preserve fresh feed in animal production and in biorefinery (Okoye et al., 2023). In these processes, lactic acid bacteria (LAB) play a key role among silage microorganisms, and the effects of exogenous LAB on silage quality have been widely studied (Wang et al., 2021). Furthermore, LAB are among the microorganisms with GRAS (generally recognized as safe) status (Fabiszewska et al., 2019). Additives are frequently used to speed up the ensiling process, prevent the growth

of harmful microorganisms, and improve the silage quality of different crops (Ivetić et al., 2024).

Silage is an excellent method of feed preservation; however, carbon dioxide, methane, and nitrous oxide produced during fermentation are significant sources of agricultural greenhouse gases (Hu et al., 2024). In light of climate change and rising temperatures, understanding the impacts of high-temperature ensiling on microbial communities is crucial, as these conditions may increase the alpha diversity of the resulting silage and enhance heterofermentative fermentation (Hernández-Perea et al., 2025). In many countries, there is a scarcity of forage for ruminant feeding due to climatic conditions and water resource shortages (Sahoo, 2018).

The technology of silage preparation involves several routine techniques, but each step carries a number of possible consequences for the quality of the resulting silage if not implemented correctly (Ivetić, 2017). The main points of risk are selecting the correct stage of plant maturity for ensiling, rapidly removing air from the plant mass in the silo, and ensuring proper covering. Changes in the silo mass occur practically as soon as the plant mass is transferred from the field to the prepared silo object. The course and intensity of these changes depend on a number of factors, but mostly on those that condition the successful development of lactic acid fermentation, such as moisture in the plant mass, an anaerobic environment, carbohydrate content, and temperature. These factors create conditions in which the desired microorganisms will dominate during fermentation of the plant mass and enable the production of quality silage with high nutritional value.

To produce high-quality silage, one must conduct a thorough assessment of the plant, microbial, and environmental factors that influence the fermentation process and, ultimately, the silage's nutrient value. Sahoo (2018) emphasized that the influence of forage characteristics (epiphytic lactic acid bacteria (LAB), buffer capacity, and sugar: buffer capacity ratio) on treatment effectiveness varied with DM content. It is essential to harvest forage at the right time, considering nutritional quality, available quantity, and climatic conditions, and then to store it properly to reduce losses. Silage corn production has significant environmental benefits, including reductions in greenhouse gas emissions, improved fertilizer use efficiency, improved soil health, and reduced environmental pollution (Zhang et al., 2025).

Choosing the right corn hybrid and other plant cultivars affects the nutritional value of silage and milk production. Optimizing harvest maturity, kernel processing, theoretical cut length, and cutting height improve or maintain the nutritive value and milk production of lactating dairy cows (Ferraretto et al., 2018). The authors point out that technological advancements have been developed and made available to dairy producers and corn growers seeking to enhance the fiber and starch digestibility of whole-plant corn silage. However, inconsistencies in silage quality may also be due to climate change.

Impact of Climate Change on Silage Preparation

Greenhouse gas emissions during ensiling are closely linked to microbial activity. Hu et al. (2024) note that studies indicate that *Lactobacillus* inhibits plant cell respiration and gas-producing bacteria by rapidly lowering the environmental pH in the early phase. Its relative

abundance is negatively associated with total gas emissions and CO₂ output (Zheng et al., 2022). Meanwhile, Enterobacteriaceae are active in the initial stages, using sugars to generate CO₂. Their relative abundance correlates positively with CO₂ production (Sun et al., 2023). Where silage microorganisms can recycle CO₂, fermented silage as animal feed has significant potential to reduce emissions, even to the point of serving as a carbon sink, through the application and manipulation of silage bacteria (Kruger et al., 2023).

Where international policy encourages farmers to adopt sustainable farming practices, emissions from silage preservation are not sufficiently documented in the European Union or United States emissions inventories to incentivize good silage preservation practices (Kruger et al., 2023). In fact, emissions from stored silage are excluded from the European inventory (European Environment Agency, 2019), whereas many factors related to silage production are inventoried in non-agricultural sectors.

The increasing frequency of extreme climate events has made the identification of stress-tolerant germplasm essential in crop breeding research (Li et al., 2024). Identifying germplasms with deep root systems enhances drought resistance by facilitating deeper water absorption (Hu et al., 2024).

Krueger et al. (2023) estimated the CO₂ emissions of corn silage based on a meta-analysis review of laboratory experiments to be $1.9 \pm 5.6\%$ (GWP₂₀) and $0.2 \pm 5.5\%$ (GWP₁₀₀) of silage dry matter. Furthermore, model results demonstrated a precedent for CO₂ recycling by silage microorganisms, which was supported by genome annotation of strains belonging to common silage species. Linear model equations for GWP₂₀ and GWP₁₀₀ with inputs and outputs in mg kg⁻¹ silage dry matter were developed, where inputs are acetic acid (A), ethanol (E), lactic acid (L), and volatile corrected dry matter loss (DV).

Linear equations are (for GWP₂₀):

$$\text{GWP}_{20} = -3626.1 - 0.04343A + 0.8011E - 0.03173L + 1.46573DV$$

And for GWP₁₀₀:

$$\text{GWP}_{100} = -8526.10 - 0.22403A - 0.11963E - 0.03173L + 1.46573DV.$$

The quality of feed crops and forage may decline due to higher temperatures and dry conditions, which alter water-soluble carbohydrate and nitrogen levels, according to Rojas-Downing et al. (2017). Increased temperatures can raise lignin and cell wall components in plants (Polley et al., 2013), reducing digestibility and nutrient availability for livestock (Polley et al., 2013; Thornton et al., 2009). Conversely, rising CO₂ levels improve forage quality more in C3 plants, which also have higher crude protein and digestibility than C4 plants (Polley et al., 2013; Thornton et al., 2009; Wand et al., 1999).

As climate change challenges plant silage cultivation, adaptation studies are vital. Temperature and precipitation shifts affect growth, development, and yield, highlighting the need for adaptation research, as maize genotypes respond differently to climatic conditions (Zhang et al., 2025).

Drought, heat waves, and groundwater shortages are changing corn cultivation worldwide (Tothi et al., 2022). The authors emphasize that silage crop preparation's sensitivity to

climate change. Corn (*Zea mays* L.) silage is a major forage source for ruminants in climates where corn is moderate to well adapted, consisting of the high energy, low-protein forage commonly used for growing and finishing beef cattle as supplemental energy for cow and calf production, for growing dairy heifers, and for lactating dairy cows, often in combination with a complementary high-protein forage such as alfalfa (*Medicago sativa* L.), (Allen et al., 2003). Aflatoxins have a significant health, nutritional, and economic impact on the nutritional chain of humans and animals. All participants in the production and food chain such as farmers, grain producers, distributors, crop processors, farmers, and consumers have consequently losses, (Ivetić et al., 2022). Direct effects include increased veterinary care costs, reduced livestock production, and continued endangered food safety for humans and animal feed (Ćosić and Ivetić, 2022).

Contamination with undesirable microbes and chemical agents is one of the major problems in silage production. The presence of yeasts and molds can negatively affect silage's nutritional value (NV) because they produce toxic compounds that are harmful to ruminants (Alonso et al., 2013). These microbes can proliferate massively once the silo is opened due to the presence of oxygen. As a result, increasing yeast and mold populations decrease aerobic stability and reduce silage stability. Mycotoxins are secondary fungal metabolites that have been detected in a variety of feed ingredients and can affect human and animal health, and animal productivity. Consuming the contaminated silage, ruminants are often exposed to mycotoxins, primarily such as aflatoxins, trichothecenes, ochratoxin A, fumonisins, zearalenone, and many others. Mycotoxins in silage can be minimized by preventing fungal growth before and after ensiling, with proper silage management to reduce mycotoxin contamination of feeds, and certain mold-inhibiting chemical additives or microbial inoculants can also reduce the contamination levels, (Ogunade et al., 2018). Apart from mycotoxins, microbial hazards include *Clostridium botulinum* (associated with cattle botulism), *Bacillus cereus*, *Listeria monocytogenes*, Shiga toxin-producing *Escherichia coli*, *Mycobacterium bovis*, and various mold species, (Driehuis et al., 2018).

Mycotoxins are secondary products of mold metabolism, which are synthesized by a series of reactions catalyzed by enzymes from a large number of biochemically simple intermediate products of primary metabolism, (Kos, 2015). Mycotoxins are produced by toxic strains of fungi that are found in food for humans and animals, (Chhaya et al., 2023). There is a constant threat to mycotoxins contamination all over the world in the nutritional chain, with a serious impact on human and animal health (Ivetić et al., 2024). Physical factors like pH, light, moisture, temperature, water, relative humidity, and atmospheric gases are responsible for aflatoxin contamination, (Ivetić et al., 2023).

To minimize the aflatoxin contamination in crop plants, various physical, chemical, and biological methods, and various breeding and genetic engineering approaches as well, have been used to minimize the toxicity of aflatoxin and reduce its level below the recommended one. Several approaches have been manifested to reduce the aflatoxin contamination in crops which include various physical, chemical, and biological methods.

Impact of Climate Change on Livestock

Livestock systems are affected by climate change primarily through rising temperatures, changes in precipitation, and increasing atmospheric carbon dioxide (CO₂) concentrations,

as well as a combination of these factors (IPCC, 2019). Temperature affects key factors in livestock production, including water availability, animal production and reproduction, and animal health (mostly through heat stress) (Rojas-Downing et al., 2017), as shown in Figure 1. Reduced feed intake is also a response to high environmental temperatures (Cheng et al., 2022).

Climate change significantly affects livestock by impacting agriculture and leading to shortages in feed resources and their quality, which, in turn, can influence growth, milk production, reproduction, metabolic activity, and disease prevalence (Sahoo, 2018). Climate change is already affecting food security. Recent studies in both large-scale and small-holder farming systems document declines in crop productivity due to rising temperatures and changes in precipitation. Evidence of climate change impacts (e.g., declines and stagnation in yields, changes in sowing and harvest dates, increased infestation of pests and diseases, and declining viability of some crop varieties) is emerging from detection and attribution studies and ILK in Australia, Europe, Asia, Africa, North America, and South America (medium evidence, robust, IPPC, 2018) (Figure 2, Table 1).

Indirect effects of climate change on livestock include (i) limited access to water, pasture, and other feed resources, (ii) health issues related to altered or new vector-borne and parasitic diseases, and (iii) competitive environmental interactions with other livestock species, (Sahoo, 2018).

By using a seven-category typology to classify and compare smallholder farmer adaptations across communities, the synthesis shows that in order to reduce their vulnerability, smallholder farmers have mostly taken action on environmental management and diversified their livelihoods through market exchange, and some have engaged in labour migration (Burnham and Ma, 2016).

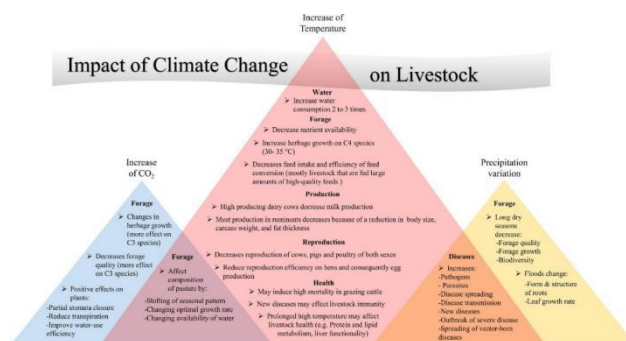


Figure 2. Impacts of Climate Change on Livestock (Rojas-Downing et al., 2017)

The review by Rojas-Downing et al. (2017) outlines key impacts of climate change on livestock: increased heat stress that causes animal mortality and affects product quality; reduced feed quality due to droughts and elevated CO₂ levels; the spread of parasites and vector-borne diseases that threaten livestock health; and the importance of adaptation and mitigation strategies. These include enhanced cooling systems in shelters and modifications to feed. The review also emphasizes the need for research in developing countries to address these challenges. Additionally, Cheng et al. (2022) highlight that implementing

adaptation measures is vital to meet the rising demand for livestock products and reduce climate change impacts.

Table 1. Climate change impacts on livestock production (Cheng et al., 2022)		
Impact type	Observed impacts	Major influential factors
Direct impact	Reduced feed intake	Increased temperature (heat stress)
	Decline in animal and meet production	
	Decreased reproductive performance	
	Negatively affected immune functions	
Indirect impact	Increased mortality	Elevated CO ₂ level
	Changes in feedstuff crop yields	
	Changes in pasture composition and forage production	Increased temperature and elevated CO ₂ level
	Changes in forage quality	
	Shrinking water availability and increasing water use	Increased temperature
	Larger seasonal variation in resource availability	More frequent extreme climate events
	Increased disease, pest, and parasite stress	Increased temperature and changes in the precipitation pattern

Feeds with low quality and digestibility lead to higher enteric emissions per unit of meat or milk, especially in low-productivity systems (Ivetić et al., 2021; Belay 2019). Enhancing feed digestibility and energy content, as well as better matching protein supply to animal needs, can be achieved through improved grazing management, selecting better pasture species, changing forage mixes, and increasing the use of feed supplements to create a balanced diet that includes crop by-products and processed crop residues. These strategies can enhance nutrient uptake, boost animal productivity and fertility, and thus reduce emissions per unit of product. However, it is important to ensure that emissions from off-farm production and processing of supplementary feeds do not exceed on-farm emission reductions (Belay, 2019). Diet adjustments, such as increasing the proportion of concentrates and improving forage quality and digestibility, offer a practical way to lower enteric CH₄ emissions and emission intensity. Nonetheless, the mitigation potential of these practices is typically limited to about 10 to 15% (Hristov, 2024).

Mitigation of enteric methane emissions is necessary to achieve these goals. Many innovative solutions are being tested and considered. Global challenges, such as enteric methane mitigation and its contribution to climate change, cannot be solved by one organization, (Ivetić et al., 2023). Addressing these challenges requires collaboration among many organizations and across different sectors, followed by cross-border and worldwide cooperation, (Ivetić et al., 2023).

Global climate change is affecting temperature, precipitation, and water availability, which directly affects agriculture and livestock productivity (Souza et al., 2023). Therefore, the expected declines in dry matter intake (DMI) and animal productivity, and changes in water intake caused by heat stress, may also affect the environmental costs of production in cattle. Emissions of GHG from livestock (by category) are shown in Figure 3.

The high-efficiency utilization of feed resources and environmental protection are two major challenges in animal husbandry. The goal of carbon neutrality by 2050 is to enhance livestock-rearing technology and contribute to a green, decarbonized society (Cai, 2025). The previously mentioned author emphasizes that this approach not only promotes harmony with nature but also fosters sustainable practices that allow for resource cycling and synergy between farming and livestock operations.

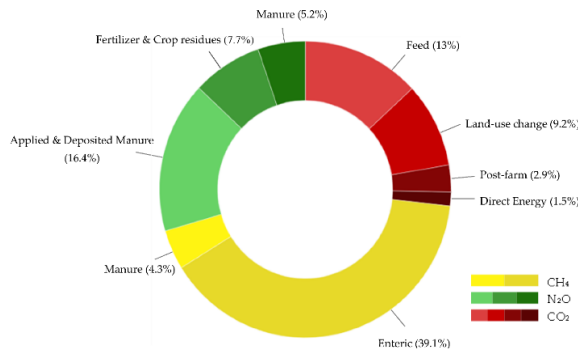


Figure 3. Emissions from livestock (by category), where methane (CH₄) emissions are portrayed in yellow, nitrous oxide (N₂O) in green, and carbon dioxide (CO₂) in red (Cheng et al., 2022) according to the data source of Gerber et al. (2013).

Preserving a greater proportion of food waste for use as livestock feed, especially as silage, would have significant environmental and socioeconomic benefits (Ivetić et al., 2022; Rodriguez et al., 2024). Many experiments have shown that adding food waste as a silage additive to treated silage reduces CH₄ emissions and nitrogen losses while decreasing DM digestibility (Zhang et al., 2025). According to Hossain (2025), environmentally, silage production minimizes crop residue waste and lowers greenhouse gas emissions by reducing the need to transport fresh feed. Using silage also helps livestock systems become more resilient to climate change by enabling adaptation to changing feed availability (Hossain, 2025). Although maize silage is widely used in animal agriculture because of its efficiency and nutritional benefits, challenges remain in optimizing quality, managing pathogens, and adapting production processes to climate change (Zhang et al., 2025).

Climate change adaptation refers to adjustments in ecological, social, or economic systems to reduce the negative impacts of climate change or enhance its positive impacts (Cheng et al., 2022). In an agricultural setting, adaptation can occur through ecological change or human action, as previously mentioned, authors noted.

CONCLUSION

By 2050, global food production must increase by 50% despite climate change threats, as projections based on population growth and food consumption patterns indicate a need to meet the population's nutritional demands. On the other hand, there is a growing threat from global climate change and its negative impact on livestock production. These changes affect silage consumption and production patterns, increasing the risk of a decline in silage nutritional value. Many innovative solutions for silage additives are under consideration

and being tested. Climate change adaptation refers to adjustments in the ensiling process and in crop cultivation to enhance silage health, safety, and quality.

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REGENERATIVE AGRICULTURE: CURRENT STATE, GOALS, AND FUTURE PERSPECTIVES

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Abstract: Regenerative agriculture has become a leading approach in transforming agrifood systems, focusing on restoring ecosystem functionality while preserving agricultural productivity. In contrast to sustainability-focused methods that typically prioritize reducing negative impacts, regenerative agriculture aims for net-beneficial results regarding soil vitality, biodiversity, climate stability, and economic resilience. Even with growing acceptance and policy attention, the notion is still variably defined, and empirical data are inconsistent. This paper integrates existing scientific literature to evaluate the condition of regenerative agriculture, its main objectives, recorded results, and future research and application viewpoints. We assess prevailing practices, environmental and socio-economic goals, along with methodological hurdles in assessing regenerative systems. We also highlight significant research gaps concerning metrics, scalability, and governance. The study finds that regenerative agriculture offers considerable promises for climate-resilient and multifunctional food systems; however, it needs standardized frameworks, extensive empirical research, and cohesive policy backing to evolve from an aspirational idea to a data-driven agricultural approach.

Keywords: Regenerative agriculture, Soil health, Agroecosystems, Sustainability transition, Ecosystem services

INTRODUCTION

During the second half of the 20th century, there was an intensification of agricultural production, which led to an increase in the yield of crops, but consequently caused negative effects on agricultural land, biodiversity, and stability of the agroecosystem (Pretty et al., 2018). According to estimates by the Food and Agriculture Organization of the United Nations (FAO, 2017), a significant loss (in %) of agricultural land worldwide shows signs of degradation, primarily due to erosion, loss of organic matter, and intensive use of chemical preparations (Blanco-Canqui et al., 2018). Approximately 25% of annually anthropogenic greenhouse gas (GHG) emissions, one-third of terrestrial acidification, and the majority of surface water eutrophication worldwide are currently caused by the global food system (Poore et al., 2018). The planet's carrying capacity will probably be exceeded if our food system keeps using fossil fuels, artificial fertilizers, synthetic pesticides, and food waste (Campbell et al., 2017). Thus, producing enough safe and nourishing food for

an expanding and affluent population within the planet's carrying capacity is humanity's greatest problem (Willett et al., 2019).

Alternative agricultural paradigms have become more well-known in response to these difficulties. These include climate-smart agriculture, agroecology, organic farming, conservation agriculture, and, more recently, regenerative agriculture (RA). Because of its clear focus on improving resilience, restoring ecosystem function, and producing net-positive environmental results in addition to productive agricultural systems, RA has become one of the most talked-about frameworks among them (LaCanne et al., 2018; Schreefel et al., 2020).

Scientists, farmers, businesses, and legislators are increasingly promoting regenerative agriculture (RA) as a means of restoring ecosystem functioning while maintaining food security. Regenerative agriculture places more emphasis on the active regeneration of soil, biodiversity, and ecosystem services than traditional sustainability methods, which concentrate on reducing adverse effects (Rhodes, 2017; LaCanne and Lundgren, 2018; Lal, 2020). However, the term's quick spread has overtaken conceptual clarity and empirical support, sparking discussions about its practical applicability and scientific foundation.

Regenerative agriculture is most accurately characterized as a system grounded in principles, rather than merely a prescriptive compilation of practices. Fundamental principles frequently acknowledged in scholarly discourse encompass:

- Sustaining continuous soil cover to safeguard against erosion and foster soil microbiota (Thierfelder et al., 2021).
- Minimizing soil disturbance through reduced or no-tillage methodologies to preserve soil structure and carbon reserves (Lal, 2020).
- Maximizing biodiversity through the implementation of crop rotations, intercropping, and agroforestry practices to enhance ecosystem resilience and nutrient cycling (Kremen et al., 2012; Hartman et al., 2018).
- Incorporating livestock to emulate natural grazing behaviors, thereby recycling nutrients and augmenting soil health (Teague et al., 2016).
- Bolstering biological processes, encompassing soil microbial activity, pollination, and pest management (Schreefel et al., 2020).

These principles distinctly separate regenerative agriculture from conventional sustainability paradigms, which predominantly emphasize impact mitigation rather than proactive ecological regeneration (Doré et al., 2011; LaCanne et al, 2018).

MATERIAL AND METHODS

Historical Background

Regenerative agriculture draws from multiple disciplinary and practical traditions. Its conceptual foundations overlap with: Agroecology, emphasizing ecological processes, system-level thinking, and socio-cultural integration (Pretty, 2008; Gliessman, 2015); Conservation agriculture, which focuses on minimal soil disturbance, soil cover, and crop rotation (Thierfelder et al., 2021); Organic farming, particularly in its reduced reliance on synthetic inputs, although RA does not require certification (Gattinger et al., 2012). Holistic

planned grazing, which model's livestock management on natural rangeland processes to restore soil and vegetation (Teague et al., 2016). Permaculture and regenerative design, emphasizing perennial systems, energy efficiency, and circular nutrient flows (Mollison, 1988; Stavi et al., 2015). The convergence of these disciplines reflects the interdisciplinary and context-specific nature of RA, making it adaptable but also challenging to standardize (Giller et al., 2021).

Goals and Objectives of Regenerative Agriculture

Soil Health Restoration - Enhancing soil quality is fundamental to Regenerative Agriculture (RA). Healthy soils deliver vital ecosystem services like nutrient cycling, water retention, and carbon sequestration. Techniques such as cover cropping, reduced tillage, and organic amendments boost soil organic matter, strengthen aggregate stability, and increase microbial diversity (Lal, 2020; Hartman et al., 2018; Pratt et al., 2020).

Climate Change Mitigation and Adaptation - Regenerative agriculture is increasingly viewed as a climate-smart strategy. RA methods can capture carbon in soils and biomass, lower nitrous oxide emissions, and build resilience against extreme weather like droughts and floods (Paustian et al., 2016; Mottet et al., 2017; Teague et al., 2016). Nonetheless, the potential for sequestration is highly specific, depending on baseline soil conditions, climate, and management intensity (Lal, 2020; Giller et al., 2021).

Biodiversity Enhancement - Boosting biological diversity serves both ecological and functional purposes. Diverse crop rotations, intercropping, agroforestry, and reduced chemical inputs aid soil organisms, pollinators, and natural pest predators (Kremen et al., 2012; Schreefel et al., 2020). These biodiversity gains support ecosystem stability, resilience, and long-term productivity.

Socio-Economic Resilience - Regenerative agriculture can boost farmer livelihoods by cutting input costs, diversifying income sources, and reinforcing local food systems (Schader et al., 2018; LaCanne et al., 2018). Its participatory and adaptive nature prompts farmers to innovate and exchange knowledge, thereby enhancing social capital and community resilience (Chambers et al., 2013).

Current Adoption and Practice Diversity

RA adoption is on the rise, though unevenly distributed. Empirical studies reveal that uptake is highest in areas with established conservation agriculture programs, access to technical knowledge, and robust market or policy incentives (Giller et al., 2021; Thierfelder et al., 2021). Common practices include cover cropping, crop rotations, reduced tillage, organic amendments, holistic grazing, and agroforestry integration (Hartman et al., 2018; Schreefel et al., 2020). However, adoption is hindered by barriers such as Short-term yield trade-offs during transition phases (Thierfelder et al., 2021); labor and management complexity, and a lack of standardized monitoring and certification frameworks (Pratt et al., 2020; Reed et al., 2019).

Scientific Debates and Research Gaps

Despite growing popularity, RA faces critical scientific and operational debates: Conceptual clarity: The absence of a standardized definition allows flexibility but increases

the risk of greenwashing (Giller et al., 2021). Evidence heterogeneity: Empirical outcomes vary depending on climate, soil type, and system design, complicating generalizations (Thierfelder et al., 2021; Mottet et al., 2017). Metrics and monitoring: There is a lack of harmonized indicators to assess soil health, biodiversity, carbon sequestration, and socio-economic impacts (Pratt et al., 2020; Schreefel et al., 2020). Scaling and policy integration: Moving from pilot studies to landscape-level adoption requires effective policy instruments, incentives, and risk-sharing mechanisms (Reed et al., 2019; Doré et al., 2011). Addressing these gaps requires long-term, systems-based research integrating ecological, agronomic, and socio-economic dimensions (Giller et al., 2021; Chambers et al., 2013; Pretty, 2008).

Current State of Regenerative Agriculture

Regenerative agriculture has been increasingly adopted globally over the past decade, with its uptake varying widely by region, crop type, and socioeconomic context. Evidence from North America, Europe, Australia, and parts of Latin America and Africa shows that RA is practiced across diverse systems, including row crops, pastures, orchards, and mixed farming systems (Giller et al., 2021; Thierfelder et al., 2021; LaCanne et al., 2018).

Regional Adoption Patterns

In North America, adoption is primarily driven by farmer-led initiatives, corporate sustainability programs, and climate-conscious markets. Key practices include cover cropping, no-tillage, integrated crop-livestock systems, and diversified rotations (LaCanne et al., 2018; Teague et al., 2016). In Europe, RA adoption is often integrated with agroecological and organic systems, emphasizing soil organic matter enhancement and biodiversity conservation. Policy incentives, such as agri-environmental schemes, have facilitated the adoption of practices (Doré et al., 2011; Schreefel et al., 2020). In Australia and New Zealand, holistic grazing and perennial pastures dominate, focusing on soil restoration and resilience in semi-arid rangelands (Teague et al., 2016; Mottet et al., 2017). In Africa and Latin America, adoption is emerging in smallholder systems, often linked to food security and climate adaptation initiatives. Practices include agroforestry, intercropping, and soil fertility management with organic inputs (Pretty, 2008; Giller et al., 2021).

Dominant Practices and Management Strategies

There are common regenerative practices identified in the literature: using cover cropping and green manures - enhancing soil fertility, reducing erosion, and increasing microbial activity (Thierfelder et al., 2021; Pratt et al., 2020). Practices with reduced or no-tillage preserve soil structure, reduce compaction, and increase carbon sequestration (Lal, 2020). Diverse crop rotations and intercropping lead to increasing nutrient use efficiency and resilience to pests and diseases (Hartman et al., 2018; Kremen et al., 2012). Agroforestry and perennial integration - stabilize soil, improve microclimate regulation, and sequester carbon (Schreefel et al., 2020; Stavi et al., 2015). Holistic livestock grazing: Improves nutrient cycling, reduces invasive species, and enhances pasture productivity (Teague et al., 2016). Organic amendments: Compost, manure, and biochar are applied to restore soil fertility and microbial communities (Lal, 2020; Gattinger et al., 2012).

Measured Outcomes

Empirical studies indicate that regenerative agriculture can deliver measurable ecological and socioeconomic outcomes, although results vary:

- Soil health: Soil organic carbon increases by 0.3-1.2 Mg C ha⁻¹ yr⁻¹ under regenerative practices, depending on soil type, climate, and implementation duration (Paustian et al., 2016; Lal, 2020).
- Water retention and infiltration: No-till and cover-cropping systems can increase water infiltration by 20-50%, improving drought resilience (Thierfelder et al., 2021).
- Biodiversity: Plant and soil microbial diversity are enhanced, leading to improved pollination, pest regulation, and nutrient cycling (Kremen et al., 2012; Hartman et al., 2018).
- Yield and productivity: Many studies report comparable or slightly reduced short-term yields during the transition period, followed by long-term stabilization or improvement (Giller et al., 2021; LaCanne et al., 2018).
- Socioeconomic outcomes: Reduced input costs, diversified income sources, and improved farm resilience have been documented, especially when supported by market or policy incentives (Schader et al., 2018; Chambers et al., 2013).

Challenges in Current Adoption

Despite its potential, RA adoption faces significant barriers, including knowledge gaps. A lack of region-specific knowledge and training can hinder adoption (Pretty, 2008; Schreefel et al., 2020). Measurement inconsistencies, particularly variability in how soil health, biodiversity, and ecosystem services are measured, make cross-study comparisons difficult (Pratt et al., 2020). Economic trade-offs: Initial yield reductions and labor requirements can deter adoption, particularly for smallholder farmers (Thierfelder et al., 2021). Policy and market limitations: Absence of standard certification frameworks and limited financial incentives reduce scalability (Reed et al., 2019).

Future Perspectives and Research Directions

A critical future step is harmonizing definitions and metrics to allow consistent monitoring, assessment, and comparison. Multi-dimensional frameworks combining soil health, biodiversity, carbon sequestration, water retention, and socio-economic resilience are required (Pratt et al., 2020; Schreefel et al., 2020). Metrics should be scalable, applicable from field to landscape levels, and sensitive enough to detect short- and long-term changes.

Most empirical studies on RA are short-term (<5 years) and geographically limited. Long-term, multi-site research can clarify the temporal dynamics of soil carbon accumulation (Paustian et al., 2016). Also, can determine resilience to climate extremes (Mottet et al., 2017) and evaluate trade-offs between productivity and ecosystem services (Giller et al., 2021).

Policy frameworks can accelerate RA adoption through payments for ecosystem services, carbon credit schemes, and subsidies for regenerative practices. Evidence-based policy

requires robust monitoring, evaluation, and reporting systems (Reed et al., 2019; Doré et al., 2011).

Emerging technologies can enhance regenerative agriculture by remote sensing and drones for monitoring soil health, crop diversity, and vegetation cover (Hartman et al., 2018). Also, it can be used as the decision-support tools for adaptive management based on real-time soil, weather, and crop data (Stavi and Lal, 2015). Data-driven can be used for giving insights for carbon accounting, biodiversity assessment, and landscape-level planning in future (Paustian et al., 2016).

Future perspectives for social and knowledge systems, it can be significantly improved by regenerative agriculture. Farmer-led innovation, co-creation of knowledge, and participatory research are essential to tailor regenerative agriculture to local contexts. Social learning networks and knowledge-sharing platforms can increase adoption, reduce risks, and foster innovation (Chambers et al., 2013; Pretty, 2008).

RESULTS AND DISCUSSION

Regenerative agriculture represents a paradigm shift from conventional or even sustainability-focused farming, emphasizing restoration rather than mere impact reduction. The synthesis of current literature shows that RA can deliver measurable ecological benefits, including improved soil health, enhanced biodiversity, and increased water retention (Lal, 2020; Hartman et al., 2018; Kremen et al., 2012). At the same time, it can support socio-economic outcomes such as diversified income, reduced dependence on chemical inputs, and long-term farm resilience (LaCanne et al., 2018; Schader et al., 2018).

Despite these promising outcomes, several critical challenges remain. First, adoption is uneven globally and context-specific, influenced by climate, soil conditions, market access, labor availability, and policy frameworks (Giller et al., 2021; Thierfelder et al., 2021). Second, the lack of a standardized definition and monitoring framework has led to conceptual ambiguity and the risk of “greenwashing” (Schreefel et al., 2020). Third, long-term, multi-site empirical evidence remains limited, making it difficult to fully quantify trade-offs between productivity and ecological gains (Paustian et al., 2016; Mottet et al., 2017).

The literature suggests that RA should not be viewed as a prescriptive set of practices but rather as a principle-driven, adaptive framework. Its integration with broader sustainability and climate-smart agricultural strategies can enhance both resilience and productivity. Policy support, knowledge co-creation, and technological innovation are essential to scale RA beyond pilot sites and early adopters. For example, digital decision-support tools, remote sensing for soil and vegetation monitoring, and farmer participatory networks can accelerate adoption and improve outcome monitoring (Hartman et al., 2018; Stavi et al., 2015).

Finally, the research community must prioritize system-level studies that link soil health, biodiversity, climate mitigation, and socio-economic outcomes. This requires interdisciplinary collaboration across agronomy, ecology, economics, and social sciences.

By establishing robust evidence, RA can move from an aspirational framework to an evidence-based strategy that contributes meaningfully to sustainable food systems.

CONCLUSION

Regenerative agriculture offers a compelling pathway to transform agricultural systems toward ecological and socio-economic sustainability. Its principle-based framework centered on soil health, biodiversity, climate resilience, and farmer well-being addresses multiple dimensions of agricultural sustainability simultaneously. Current evidence shows that RA practices can enhance soil organic carbon, microbial diversity, water retention, and landscape multifunctionality, although outcomes are highly context dependent. Future adoption and scaling will require: Standardized definitions and metrics for consistent evaluation. Long-term, multi-site research to quantify ecological and socio-economic outcomes. Policy frameworks and market incentives to reduce adoption barriers and encourage ecosystem service provision. Technological and social innovations to support adaptive management and farmer knowledge networks. With these components, regenerative agriculture can evolve from a conceptually promising framework into a scientifically grounded and practically viable approach for sustainable, climate-resilient, and profitable food systems.

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REDUCING PESTICIDE USE IN VITICULTURE AND NEW PERSPECTIVES FOR THE IMPLEMENTATION OF INTEGRATED PEST MANAGEMENT - AN EXAMPLE OF GB4IPM PROJECT

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Abstract: Viticulture is among the most pesticide-intensive agricultural systems due to the high susceptibility of grapevine to fungal diseases and the strong dependence of disease development on climatic conditions. Increasing regulatory pressure to reduce pesticide use, together with accelerating climate change impacts, requires a fundamental rethinking of plant protection strategies in vineyards. Integrated Pest Management (IPM) offers a systemic framework for reducing chemical inputs while maintaining productivity and quality; however, its effective implementation remains uneven across Europe. This paper provides a comprehensive synthesis of plant protection tools for reducing pesticide use in viticulture, with a particular focus on disease-resistant grapevine varieties, adaptive disease management under climate change, and region-specific implementation of IPM strategies. Special attention is given to Serbia and the Western Balkans as state-of-the-art case vignettes representing high disease pressure, fragmented production structures, and strong dependence on advisory systems. The analysis integrates recent scientific literature with emerging European research perspectives, highlighting pathways toward resilient, knowledge-based viticulture systems.

Keywords: Viticulture, Integrated pest management, Pesticide reduction, Disease-resistant grapevine varieties, Climate change, Plant protection

INTRODUCTION

Viticulture occupies a distinctive position within European agriculture. Despite covering a relatively small proportion of agricultural land, vineyards account for a disproportionately high share of fungicide use, primarily due to their susceptibility to downy mildew (*Plasmopara viticola*), powdery mildew (*Erysiphe necator*), and Botrytis bunch rot (*Botrytis cinerea*). Historically, disease control in grapevine production has relied on frequent preventive fungicide applications, often applied according to calendar-based schedules rather than real-time risk assessment.

While this approach has ensured yield stability, it has also contributed to environmental contamination, non-target effects on biodiversity, and the emergence of fungicide-resistant pathogen populations. At the same time, climate change is profoundly altering disease epidemiology, grapevine phenology, and production risk across Europe. Rising temperatures, modified precipitation regimes, and increasing weather variability challenge

the effectiveness of traditional plant protection strategies and intensify uncertainty in disease management.

In response to these challenges, Integrated Pest Management has emerged as the dominant conceptual framework for sustainable plant protection. IPM emphasizes the combination of genetic resistance, agronomic practices, monitoring, and targeted chemical interventions. However, the practical realization of IPM in viticulture remains constrained by biological, structural, and socio-economic factors. This paper examines the state of the art of plant protection tools for reducing pesticide use in viticulture and discusses new perspectives for IPM implementation under climate change, with particular emphasis on continental and sub-continental production contexts.

Disease Pressure and Climate Change as Structural Drivers of Pesticide Dependence in Viticulture

Viticulture is structurally exposed to high levels of biotic stress due to the intrinsic susceptibility of grapevine (*Vitis vinifera* L.) to a limited number of highly aggressive fungal pathogens, most notably downy mildew (*Plasmopara viticola*), powdery mildew (*Erysiphe necator*), and Botrytis bunch rot (*Botrytis cinerea*). These pathogens possess epidemiological characteristics that enable rapid population growth and epidemic development under favourable environmental conditions, often within short temporal windows. As a result, disease outbreaks can cause severe yield losses and quality degradation if not effectively controlled, placing grapevine production among the most risk-sensitive perennial cropping systems in temperate regions.

The dependency of viticulture on chemical plant protection products is therefore not accidental but structurally embedded in the interaction between pathogen biology and climatic drivers. Downy mildew epidemics are closely linked to rainfall events, leaf wetness duration, and moderate temperatures, conditions that frequently coincide during spring and early summer in large parts of Europe. Powdery mildew, by contrast, develops independently of free water and can proliferate under a broad range of temperature conditions, creating a persistent baseline disease pressure even in relatively dry seasons. Botrytis bunch rot further compounds disease risk by affecting both yield quantity and wine quality during flowering and ripening stages, particularly under humid conditions. The coexistence of these pathogens creates a cumulative and overlapping disease pressure that historically justified preventive and repeated fungicide applications throughout the growing season (Gessler et al., 2011; Pertot et al., 2017).

Climate change has emerged as a critical factor reshaping this already complex phytopathological landscape. Rather than uniformly increasing or decreasing disease pressure, climate change alters the temporal dynamics, intensity, and predictability of epidemics. Rising average temperatures, warmer winters, and extended growing seasons enhance pathogen overwintering survival and increase the availability of primary inoculum early in the season. Earlier budburst and accelerated phenological development expose young, highly susceptible tissues to infection during periods when pathogen pressure is already present. At the same time, changes in precipitation regimes characterized by longer dry periods interrupted by intense rainfall events create conditions for sudden and severe

disease outbreaks that are difficult to anticipate using traditional calendar-based protection strategies (Salinari et al., 2006; Jones et al., 2005).

These climatic shifts increase interannual variability and uncertainty, which in turn reinforces pesticide dependence. Under uncertain disease risk, growers tend to adopt conservative protection strategies to minimize economic losses, often leading to prophylactic treatments even in seasons with moderate disease pressure. This risk-averse behaviour is particularly pronounced in perennial crops such as grapevine, where production losses have long-term economic consequences. As a result, climate change does not automatically lead to reduced pesticide use, but may paradoxically increase spray frequency in some contexts, especially where adaptive decision-support tools and alternative protection strategies are not fully implemented.

The structural nature of pesticide dependence in viticulture has been widely recognized in recent scientific literature and is increasingly framed as a central bottleneck in the transition toward sustainable plant protection. Pertot et al. (2017) emphasized that the persistence of high fungicide inputs in vineyards reflects systemic constraints rather than a lack of available tools, pointing to the need for integrated approaches that address both biological and decision-making drivers of pesticide use. Within this framework, disease-resistant grapevine varieties have gained prominence as a key leverage point for disrupting the pathogen-climate-pesticide nexus.

Recent European research initiatives, including the scientific work coordinated by INRAE within the GrapeBreed4IPM framework, have highlighted the potential of resistant varieties to fundamentally alter disease management paradigms in viticulture. By reducing baseline infection pressure, genetic resistance enables a shift from reactive, input-intensive protection toward adaptive, risk-based management strategies. Monitoring initiatives coordinated within this scientific context have demonstrated that resistant varieties can substantially reduce fungicide applications while maintaining agronomic performance, particularly when resistance is combined with appropriate canopy management and monitoring practices (Miclot et al., 2022; Schneider et al., 2019). GB4IPM have further emphasized the importance of structured deployment and monitoring to assess resistance durability and avoid over-reliance on single resistance mechanisms.

Importantly, the effectiveness of resistance-based strategies is strongly conditioned by climatic context. In regions characterized by sustained humidity and recurrent infection cycles, such as continental and sub-continental viticulture zones, resistance provides not only a reduction in average disease pressure but also a buffer against climate-driven variability. This buffering effect becomes increasingly relevant under climate change scenarios that favour unpredictability over gradual shifts in mean conditions (Fraga et al., 2016). Consequently, genetic resistance should not be viewed as a static trait, but as a dynamic component of adaptive plant protection systems.

Taken together, disease pressure and climate change function as intertwined structural drivers of pesticide dependence in viticulture. Addressing this dependence requires more than incremental optimization of chemical control; it necessitates a systemic redesign of plant protection strategies that integrates genetic resistance, adaptive management, and knowledge-based decision-making. The growing body of scientific evidence supports the

view that such integration is not only technically feasible, but essential for achieving durable pesticide reduction under current and future climatic conditions.

Plant Protection Tools for Reducing Pesticide Use in Viticulture

Among available plant protection tools, disease-resistant grapevine varieties represent the most structurally transformative option for reducing pesticide use. By incorporating genetic resistance to key fungal pathogens, these varieties directly lower infection pressure and reduce the baseline need for chemical interventions. Numerous studies have demonstrated that resistant varieties can achieve substantial reductions in fungicide use, particularly against downy and powdery mildew, without compromising yield stability.

However, resistance is not absolute. Its durability depends on genetic architecture, pathogen adaptation, and management context. Consequently, resistant varieties must be integrated into broader IPM strategies rather than treated as standalone solutions. Agronomic and cultural practices such as canopy management, pruning, and shoot positioning further contribute to disease suppression by modifying vineyard microclimate and reducing leaf wetness duration. Improved canopy aeration has been shown to significantly reduce the severity of downy mildew and Botrytis, thereby enabling additional reductions in fungicide use.

Monitoring and risk-based decision-making represent another critical component of pesticide reduction strategies. Disease forecasting models and decision-support systems integrate weather data, phenological stages, and pathogen biology to optimize intervention timing. When effectively implemented, such tools reduce unnecessary treatments and improve fungicide efficiency. Nevertheless, their adoption remains uneven, particularly in regions characterized by fragmented production structures and limited access to precision agriculture technologies.

Integrated Pest Management in viticulture should be understood not as a single technology, but as a systemic transition from preventive, input-intensive protection toward adaptive, knowledge-based management. Effective IPM requires the alignment of genetic resistance, agronomic practices, monitoring, and targeted chemical interventions within a coherent strategy.

This transition is particularly challenging in viticulture due to high disease pressure and risk aversion among growers. Nevertheless, evidence suggests that IPM systems integrating resistant varieties and risk-based decision-making can achieve substantial reductions in pesticide use while maintaining economic viability. The key challenge lies in translating scientific knowledge into region-specific, practically applicable solutions.

Serbia and the Western Balkans as State-of-the-Art Case Vignettes

Viticulture in Serbia and the Western Balkans represents a scientifically informative case for examining the implementation of Integrated Pest Management (IPM) under conditions of persistently high disease pressure and increasing climatic uncertainty. The region is situated within a continental to sub-continental agro-climatic zone characterized by moderate to high annual precipitation, pronounced intra-seasonal variability, and frequent

rainfall events during spring and early summer. These conditions generate a structurally elevated baseline risk for fungal diseases, making disease management one of the most critical and resource-demanding components of grapevine production.

Unlike Mediterranean viticulture, where disease pressure is often episodic and closely linked to specific rainfall events, the Western Balkan context is characterized by recurrent infection cycles and extended periods of leaf wetness. Consequently, disease outbreaks are not exceptional events but an inherent feature of the production system. This epidemiological setting promotes conservative, preventive fungicide use and reinforces long-term chemical dependency, particularly in years with unstable weather patterns.

The most economically significant diseases affecting vineyards in this region are downy mildew (*Plasmopara viticola*), powdery mildew (*Erysiphe necator*), and Botrytis bunch rot (*Botrytis cinerea*). In addition, black rot (*Guignardia bidwellii*) represents a recurrent threat in specific locations and years, particularly under warm and humid conditions. Downy mildew remains the primary driver of fungicide use in continental and sub-continental viticulture, as its development is strongly dependent on rainfall events, leaf wetness duration, and moderate temperatures conditions that frequently coincide during the early stages of the growing season. Powdery mildew, in contrast, is less dependent on rainfall and can develop across a broad temperature range, maintaining baseline disease pressure even during relatively dry years. Botrytis bunch rot further compounds disease risk by affecting both yield quantity and wine quality during flowering and ripening, especially under humid conditions.

The coexistence of these pathogens creates a multi-disease pressure environment in which control strategies must be continuous and largely preventive. As a result, vineyards traditionally rely on repeated fungicide applications, often exceeding 10-12 treatments per season in years with high disease pressure, placing viticulture among the most pesticide-intensive agricultural sectors. This structural dependence on chemical control reflects not only pathogen biology but also the high economic risks associated with production losses in perennial crops.

Climate change has emerged as a decisive factor altering disease pressure patterns in the Western Balkans. Long-term climatic trends indicate rising average temperatures, increased frequency of heat waves, and shifts in precipitation distribution, characterized by longer dry periods interrupted by intense rainfall events. These changes affect both grapevine physiology and pathogen life cycles. Warmer winters enhance pathogen overwintering survival, increasing the availability of primary inoculum at the beginning of the growing season, while earlier budburst exposes young, highly susceptible tissues to infection during periods of elevated disease risk.

At the same time, extreme rainfall events create highly favorable conditions for rapid pathogen spread, often overwhelming traditional calendar-based protection strategies. Numerous studies have demonstrated that climate change does not necessarily reduce disease pressure but rather increases its variability and unpredictability, thereby complicating disease management and increasing production risk (Gessler et al., 2011; Salinari et al., 2006). Under such conditions, decision-making based solely on historical experience becomes increasingly unreliable.

In Serbia and the Western Balkans, climate-driven disease variability translates directly into heightened vulnerability, particularly for small and medium-scale growers. Structural fragmentation of vineyard holdings predominantly small, family-operated units with limited mechanization and restricted access to capital-intensive technologies limits the capacity to absorb losses or invest in advanced monitoring and decision-support tools. As a consequence, growers rely heavily on generalized advisory recommendations, reinforcing conservative protection strategies and limiting opportunities for input optimization. Advisory services therefore play a decisive role in shaping plant protection practices and represent a critical leverage point for IPM implementation in the region.

Disease-resistant grapevine varieties are currently only marginally adopted in Serbia and most Western Balkan countries. Their limited diffusion reflects a combination of strong attachment to traditional and autochthonous varieties, uncertainty regarding wine typicity and market acceptance, and limited availability of planting material. Nevertheless, the potential benefits of resistant varieties are particularly pronounced under the sustained disease pressure characteristic of this region. Even partial resistance can significantly reduce infection intensity, delay epidemic development, and lower the number of required fungicide applications, resulting in substantial reductions in chemical inputs.

Climate change further amplifies the relevance of resistance-based and adaptive IPM approaches. Heat and drought stress can weaken grapevine defense mechanisms, increasing susceptibility to opportunistic pathogens and secondary infections. The interaction between abiotic and biotic stressors adds an additional layer of complexity to disease management and challenges the stability of conventional protection systems. In this context, genetic resistance provides an important buffer against climate-driven variability, enhancing system resilience and reducing reliance on reactive chemical interventions.

The described disease–climate interactions reinforce the structural dependence of viticulture on chemical plant protection products. Despite advances in fungicide formulation and application technology, chemical control remains the dominant disease management strategy in the region. However, increasing regulatory pressure to reduce pesticide use, coupled with growing societal concerns regarding environmental and human health impacts, limits the long-term sustainability of this approach. Repeated fungicide applications contribute to the accumulation of residues in soil and water bodies, negative effects on non-target organisms and vineyard biodiversity, and increased risk of pathogen resistance to active substances. These concerns are particularly acute in the Western Balkans, where viticulture is often embedded in ecologically sensitive landscapes and rural areas with high socio-economic dependence on agriculture.

From a scientific perspective, initiatives such as GrapeBreed4IPM contribute to addressing these challenges by advancing understanding of durable resistance under sustained disease pressure and by embedding continental viticulture contexts into broader European research frameworks. This integration helps bridge the gap between innovation development and practical applicability in regions where long-term empirical data on resistant variety performance and adaptive IPM strategies remain scarce.

Disease-Resistant Grapevine Varieties Under Changing Climate Conditions

Disease-resistant grapevine varieties represent a strategic response to the combined challenges of climate change and disease pressure. By incorporating genetic resistance to

key fungal pathogens, these varieties reduce the baseline infection risk and allow for significant reductions in fungicide use. Under climate change scenarios characterized by increased variability, resistance offers an additional advantage: it provides a buffer against unexpected disease outbreaks, enhancing system resilience. Nevertheless, resistance is not absolute and must be managed carefully to avoid resistance breakdown due to pathogen adaptation.

In this context, the integration of resistant varieties into region-specific management systems is critical. Resistance must be complemented by appropriate canopy management, monitoring, and reduced-input strategies to ensure long-term effectiveness. The Western Balkans, with their variable climatic conditions, represent a valuable testing ground for assessing resistance durability under stress.

Given the complexity of disease dynamics under climate change, advisory systems play a central role in translating scientific knowledge into practice. In Serbia and the Western Balkans, advisory services are often the primary source of guidance for small and medium-scale growers, particularly in relation to disease management decisions.

Adaptive disease management requires:

- continuous monitoring of climatic conditions and disease risk,
- interpretation of complex information for practical decision-making,
- confidence to reduce chemical inputs without compromising yield and quality.

Strengthening advisory capacity is therefore essential for enabling growers to transition from calendar-based protection toward more adaptive, knowledge-based strategies that leverage genetic resistance and integrated management.

Regional Relevance in the European Context

The disease pressure and climate challenges observed in Serbia and the Western Balkans are not isolated phenomena but reflect broader trends affecting European viticulture. However, the region's combination of high disease pressure, climatic variability, and structural fragmentation amplifies these challenges, making it particularly informative for evaluating sustainable disease management pathways.

Insights gained from this region contribute to a better understanding of how viticulture systems can adapt to climate change while reducing chemical dependence. They underscore the need for context-specific solutions that integrate genetic, agronomic, and institutional dimensions.

The synthesis presented in this paper underscores that future IPM strategies in viticulture must move beyond incremental input reduction toward systemic redesign. Genetic resistance should be prioritized as a foundational element of plant protection systems, complemented by adaptive agronomic practices, monitoring, and targeted chemical use. Strengthening advisory and knowledge-transfer mechanisms is essential, particularly in fragmented production landscapes.

Climate change reinforces the need for flexible, region-specific IPM strategies. As climatic gradients converge and disease dynamics become more unpredictable, resilient, knowledge-based systems outperform rigid, calendar-based protection programs. The successful implementation of IPM therefore depends on the integration of biological, agronomic, and institutional dimensions.

CONCLUSION

Reducing pesticide use in viticulture is both an environmental necessity and a technical challenge shaped by disease biology, climate change, and production structure. Integrated Pest Management provides a robust framework for addressing these challenges, but its success depends on the effective integration of multiple plant protection tools. Disease-resistant grapevine varieties, combined with agronomic practices, monitoring, and adaptive decision-making, represent a viable pathway toward sustainable viticulture. The case of Serbia and the Western Balkans illustrate that even under high disease pressure, pesticide reduction is achievable through systemic approaches grounded in regional realities. Future progress will depend on coordinated efforts across research, advisory services, and policy domains.

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CONSEQUENCES OF THE TRANSFORMATION OF REGIONAL SPATIAL PLANS IN THE REPUBLIC OF CROATIA ON INVESTMENT IN AGRICULTURE, VIEWED THROUGH THE PRISM OF THE LAW OF THE FIFTH DISCIPLINE

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Abstract: The development of a particular area is conditioned by spatial planning regulations. Spatial planning is based on an integrated assessment of space in order to enable the improvement of technical and social infrastructure through the management of spatial resources. Spatial planning is a visionary task, as it relies on anticipating future development needs. Managing space according to the principle of an integrated approach creates conditions for social and economic development, environmental protection, and the rational use of natural and historical assets. On the other hand, investment represents the process of allocating tangible and intangible assets into specific business activities with the aim of creating new value. This process is conditioned not only by market circumstances, but also by legal constraints. For this reason, it is necessary to examine all limitations that impose a burden on potential investors intending to invest their resources in the construction of agricultural-purpose buildings. Using a methodological approach based on comparative analysis, spatial-planning indicators will be examined, while methods of multi-criteria decision-making, correlation, and regression will be used to relate variables such as the volume of investment, the number of building permits for agricultural buildings and facilities, and the number of business zones, in order to determine the significance of their interrelationships. Through inductive analysis, general conclusions will be drawn regarding the effects of investments on the social community, and the importance of applying systems thinking in spatial planning decision-making processes will be highlighted. The aim of this paper is to demonstrate the economic significance of transformations in spatial planning at the regional level, viewed through the laws of the Fifth Discipline, and to analyze the long-term consequences of specific decisions on investments in agricultural buildings and facilities.

Keywords: Spatial plans, Laws of the fifth discipline, Investments, Agriculture

INTRODUCTION

Spatial planning is based on a comprehensive assessment of space and the environment to create a foundation for the most favorable management of natural and anthropogenic areas and to identify solutions that enable improvements in technical and social infrastructure under given natural, social, and economic conditions (Healey, 2006). Particular emphasis

is placed on anticipating future development needs while giving due consideration to the specific characteristics of space and the results of research on demographic trends (Hostovsky, 2000). Spatial planning is a multidisciplinary and continuous process, the outcome of which consists of spatial plans as the most effective regulatory instruments for environmental protection (Alexander et al., 2007). The transformation of spatial planning in Croatia is rooted in the Physical Planning Act (Official Gazette Nos. 153/2013, 65/2017, 114/2018, 39/2019, 98/2019, 67/2023). This transformation aims to modernize the system, increase efficiency and transparency, and align with European standards. It enables faster adoption, implementation, and monitoring of plans, improving spatial management. Key reasons include digitalization, informatization, alignment with the new Act, better efficiency, plan coordination, transparency, and monitoring. Essentially, the transformation seeks to create a digital framework for better management and spatial development. According to the Act, the fundamental objectives of spatial planning can be summarized as follows:

- balanced spatial development aligned with economic, social, and environmental foundations, respecting spatial sustainability and the rational use of space,
- integration of the national territory into European spatial planning systems,
- coordinated and complementary distribution of various human activities in space to ensure functional and harmonious community development while protecting the integral values of space,
- well-organized allocation and development of construction land through high-quality and humane development of urban and rural settlements, the development of green infrastructure, and the provision of a safe, healthy, and socially functional living and working environment,
- provision, functional accessibility, and use of services and facilities for the needs of different population groups, especially children, the elderly, and people with reduced abilities and mobility.

Local self-government units adopt spatial plans within their territorial jurisdiction. This enables more efficient use of space. Because resources are scarce, spatial planning should guide natural resource use toward activities that create new value (Ehler et al., 2009). Spatial plans should serve as a basis for creating a vision of the future. At the same time, they must not rigidly delimit the current material and institutional structure (Portman, 2011). For these reasons, the spatial planning process tries to consider socio-economic, natural, cultural-historical, and landscape values (Healey, 2006). Spatial development, as a set of activities, ensures the management of space as a particularly valuable and limited good of an organized community (Alexander et al., 2007). Through spatial management, conditions are created for social and economic development, environmental protection, and the rational use of natural and historical assets, based on the principle of an integrated planning approach (Allmendinger et al., 2009). This process includes the analysis and determination of general development goals, the introduction of organizational and legal measures, control of construction implementation, and monitoring of the functioning of built structures (Haughton et al., 2004). High-quality sustainable development is based on the synergy of two opposing concepts of spatial management (Nadin, 2007):

- a static concept (land registry and cadaster), which must guarantee stability, immutability of geometry, and ownership rights,

- a dynamic concept (spatial planning), conditioned by economic development programs and urbanistic or agrarian design projects for the area of the local self-government unit. Through the dynamic concept and high-quality spatial planning documents, the value of all included real estate can be significantly increased.

A vision of spatial development without systems thinking will have no functional meaning, as the assessment of current reality would be conducted without an analytical approach. Systems thinking requires the disciplines of building a shared vision, team learning, and personal mastery in order to understand potential (Checkland, 1991). Building a shared vision creates advantages over a longer time horizon. Mental models focus on the openness needed to uncover deficiencies in our current understanding of the world (Flood et al., 1996). Team learning develops the ability of groups to observe and understand the broader picture that transcends individual perspectives. Personal mastery creates individual motivation for continuous learning about how our actions affect the world (Senge, 1990). The laws of the Fifth Discipline help approach problems in a thorough and analytical manner. Through his research, Peter Senge defined ten laws of the Fifth Discipline:

- Today's problems come from yesterday's solutions,
- The harder you push, the harder the system pushes back,
- Behavior grows better before it grows worse,
- The easy way out usually leads back in,
- The cure can be worse than the disease,
- Shifting the burden to the intervener,
- You can have your cake and eat it too but not at once,
- Faster is slower,
- Cause and effect are not closely related in time and space,
- Dividing an elephant in half does not create two small elephants.

Due to its complexity, investment represents a process that can generate negative effects as a result of incorrect decisions (Holland et al., 2010). Therefore, investment cannot and must not be a spontaneous process, as this leads to poorly considered decisions (Hirt et al., 2005). An increase in capital investments in buildings, equipment, infrastructure, and similar assets raises business potential (Dunning, 1972). The causes of current problems are often confusing; therefore, it is necessary to examine present solutions rooted in the past in order to understand why problems have emerged. Compensating feedback that arises from intensified intervention in a problem is reflected through even stronger resistance of the system itself (Litterman, 2003). Compensating feedback often includes delays the time between short-term benefits and long-term damage which results in temporary, symptomatic solutions. Several years may pass before the problem reappears or a new, even more severe one emerges (Senge, 1990). Symptomatic solutions are temporary and short-lived, unlike fundamental solutions, which are lasting and final. For this reason, the aim of this paper is to demonstrate the economic significance of transformations in spatial planning at the regional level, viewed through the laws of the Fifth Discipline, and to examine the long-term consequences of specific decisions on investments in agricultural production.

MATERIAL AND METHODS

The research on the implementation of the transformation of spatial plans at the regional level was conducted with the aim of analyzing the scope and dynamics of investments in agricultural facilities during 2023 and 2024. Since investment represents a process of allocating tangible and intangible assets and is conditioned by the legal framework regulating land use, this topic requires a thorough and systematic approach. The study employed a quantitative approach based on secondary analysis of official data, combined with inductive reasoning and a descriptive-analytical method. Data were collected through a survey questionnaire addressed to counties, as well as through a review of the websites of the Ministry of Physical Planning, Construction and State Assets, the State Geodetic Administration, and the Croatian Bureau of Statistics. These sources were selected due to their methodological reliability and public availability. The data includes general economic indicators, information on land use, and data on the volume of investments. Quantitative indicators are presented in tables and charts. For comparison purposes, the data were normalized according to cost structures and their values.

The analysis included:

1. Comparative analysis - comparison of data according to economic indicators and the intensity of land use,
2. Statistical correlation test of two variables for hypothesis testing:
 - that there is no significant correlation between land-use efficiency and investments, i.e., $H_0: p = 0$,
 - that there is a relationship between land-use efficiency and investments, i.e., $H_1: p \neq 0$,
3. Statistical spatial regression analysis, describing the relationship between the independent variable (x) and the dependent variable (y) using the linear equation $y = ax + b$,
4. Multi-criteria decision-making, used to rank investments in space and compare data on land-use purpose and the volume of investments,
5. Inductive analysis - deriving general conclusions on the effects of investments on local development and the local community.

The analytical framework is based on the assumption that spatial plans are a fundamental prerequisite for attracting investments and that they should positively influence:

- operational efficiency,
- financial rationality,
- transparency of governance.

Through a conceptual model, three dimensions are linked: the degree of digital transformation of spatial plans, the intensity of investment attraction, and the achieved financial and social benefits, which were compared with the laws of the Fifth Discipline using the methods described above.

Table 1. Spatial planning indicators influencing investment attraction

Indicator	Country ranking /141 (2023)	
	2023.	2024.
Efficiency of the legal framework in challenging regulations	11	10
Burden of government regulation	38	32
Efficiency of the legal framework in dispute resolution	15	17
E-participation	94	97
Property right	80	85
Land administration quality	119	121
Adaptability of the legal framework to digital business models	31	28
Road connectivity	98	92
Road infrastructure quality	121	130
Access to electricity	136	139
Quality of electricity supply	97	96
Water supply reliability	101	116
Cost of starting a business	77	73
Average	78	80

Source: Prepared by the author based on data from the OECD and The Global competitiveness Report 2023-2024 years

The analyzed indicators present values that influence the implementation of spatial planning provisions for the years 2023 and 2024. Out of a maximum possible ranking value of 141 (representing the total number of countries included in the analysis), the Republic of Croatia is positioned between ranks 78 and 80, placing it in the middle of the scale. The data indicate that the Republic of Croatia achieves its weakest results in the areas of legal regulation, the efficiency of the legal system, and the burden of government regulation while, on the other hand, its strongest position is observed in the quality of infrastructure conditions. The analyzed indicators have a direct impact on the attraction of investments. Data on the volume of attracted investments in cities are presented in the following table.

Table 2. Overview of the total volume of investments and investments in municipal infrastructure, and a comparative overview of the number of building permits and the number of business zones during 2023 and 2024 years

County	Investments in agricu. facilities (EUR)	Investments in municipal infrastructure (EUR)	Number of building permits for agricultural facilities	Numb. of business zones	Investments in agricultural facilities (EUR)	Investments in municipal infrastructure (EUR)	Number of building permits for agric. facilities	Number of business zones
	2023.				2024.			
Zagreb County	65.505,45	3.853,26	8.057	126	68.125,67	3.736,19	8.106	120
Krapina Zagorje	1.618,40	95,20	1.244	51	1.683,14	92,31	1.268	51
Sisak Moslavina	279,45	16,44	1.725	53	2.766,93	151,75	1.731	53
Karlovac	1.460,75	85,93	1.114	44	1.446,29	79,32	1.121	45
Varaždin	1.827,04	107,47	1.259	45	1.900,12	104,21	1.262	45
Koprivnica Križevci	1.473,14	86,66	1.364	60	1.532,06	84,02	1.358	60

Bjelovar Bilogora	1.150,18	67,66	1.027	55	1.196,18	65,60	1.037	55
Primorje G. Kotar	5.734,21	337,31	1.979	40	5.963,58	327,06	1.996	40
Lika-Senj	406,29	23,90	983	40	403,87	22,15	969	40
Virovitica Podravina	600,85	35,34	1.106	45	624,88	34,27	1.125	45
Požega Slavonia	474,37	27,90	1.387	44	493,35	27,06	1.374	45
Brod Posavina	925,96	54,47	1.801	49	963,00	52,81	1.819	52
Zadar	2.145,77	126,22	1.225	35	2.231,60	122,39	1.241	38
Osijek Baranja	2.509,94	147,64	1.769	60	2.610,34	143,16	1.806	62
Šibenik Knin	1.350,07	79,42	1.497	45	1.404,07	77,00	1.494	45
Vukovar Srijem	1.432,70	84,28	1.235	57	1.421,33	77,95	1.252	60
Split Dalmatia	7.839,76	461,16	1.339	45	8.153,35	447,15	1.363	50
Istria	6.102,57	358,97	1.067	37	6.346,67	348,07	1.048	37
Dubrovnik Neretva	1.663,88	97,88	933	32	1.730,44	94,90	969	35
Međimurje	1.560,50	91,79	1.132	45	1.622,92	89,01	1.166	48

Source: Prepared by the author based on data from the Croatian Bureau of Statistics, the Ministry of Physical Planning and Construction, and the State Geodetic Administration for the period 2023-2024. years

The values presented in the table indicate that the volume of investment increased by an average of 4% during the period analyzed. The highest volume of investments was recorded in the City of Zagreb, while the lowest was observed in Gospić. Cities in coastal Croatia Split, Rijeka, and Pazin lead in terms of investment volume, whereas the lowest levels of investment were recorded in mountainous regions of Croatia. A similar pattern is observed with regard to investments in municipal infrastructure.

The data further show that the largest number of building permits was issued in the City of Zagreb, which also has the highest number of business zones. Dubrovnik and Gospić recorded the lowest number of issued building permits and have the fewest business zones, which can be attributed to the fact that these counties are not predominantly oriented toward agricultural activities.

The values from Tables 1 and 2 will be used as input material for further analysis in this paper. The results section will present spatial planning indicators that influence the attraction of investments and will examine the relationship between the volume of investments, the number of building permits, and the number of business zones.

RESULTS AND DISCUSSION

The following chart presents, using a multi-criteria decision-making approach, the indicators that influence the attraction of investments in the agricultural sector.

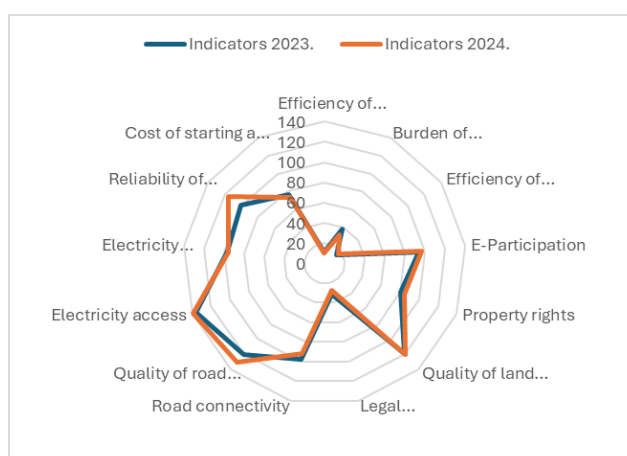


Figure 1. Spatial planning indicators influencing the attraction of investments in agricultural production development a comparative overview for the period 2021-2024 years
Source: Prepared by the author based on data from Table 1.

The data from the chart indicate that the factors most slowing the construction of agricultural capacities are the efficiency of the legal framework in challenging regulations and the efficiency of the legal framework in dispute resolution. This suggests that the legal system is slow, inefficient, and risky for investors. Economic policy measures should be directed toward more efficient business operations, increasing economic efficiency, improving the competitiveness of agricultural and food production and processing, and promoting environmentally sustainable and energy-efficient agricultural activities.

To investigate the relationship between total investments and investments in municipal infrastructure, a correlation test between the two variables was conducted. The correlation coefficient is 0.88, indicating a strong positive relationship. At a significant level of 0.05, there is a statistically significant positive correlation between total investments and investments in municipal infrastructure. The test statistic value is 2.7764; since this value is greater than zero, the null hypothesis (H_0 : no significant correlation between land-use efficiency and investments) is rejected, and the alternative hypothesis (H_1) is accepted.

The following chart presents a regression model illustrating the relationship between the number of issued building permits and the volume of investments in agricultural facilities.

The regression model indicates that if the number of building permits issued (variable x) were 0, the expected volume of investments would be €2,777.4 thousand. If the volume of investments increases by €1,000, the expected number of building permits issued for the construction of agricultural capacities would be 1.7497. Using the global Moran's I index as a spatial statistics tool, the spatial relationship can be measured specifically, how similar or different the values of total investment volume, the number of building permits, and business zones are relative to neighboring counties. The results are presented in the following chart.

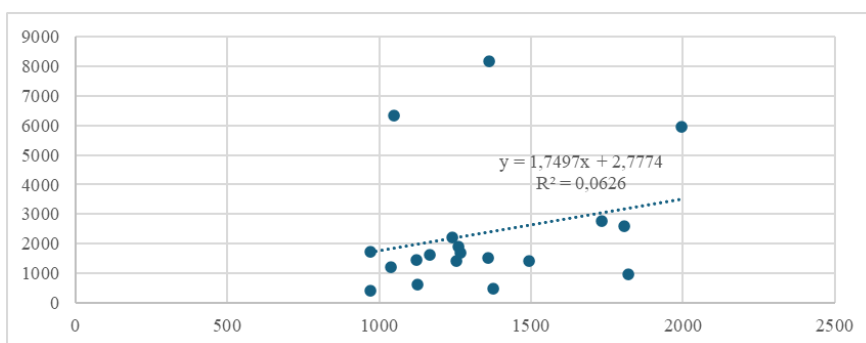


Figure 2. Regression analysis of the relationship between the number of issued building permits and the volume of investments. Source: Prepared by the author based on data from Table 2.

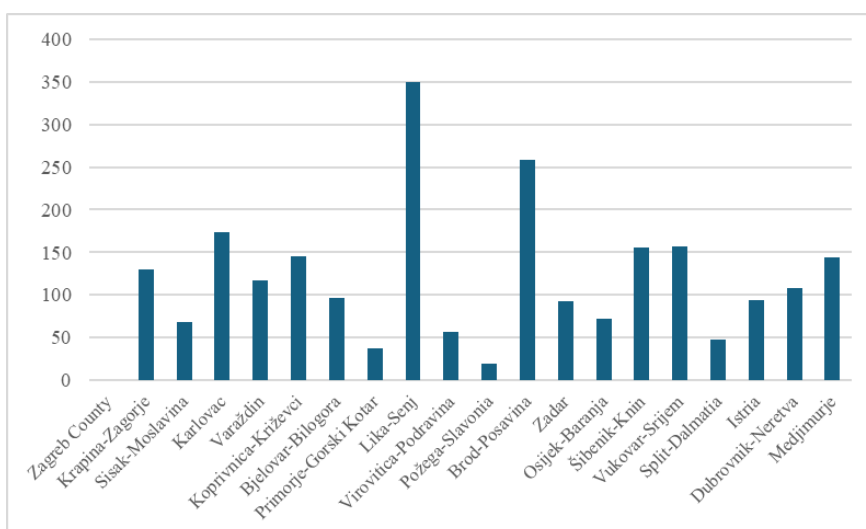


Figure 3. Global Moran's I index from multi-criteria decision-making for selecting the most attractive locations for investment. Source: Prepared by the author based on data from Table 2.

In the conducted analysis, using matrix summation, the value data indicate the presence of spatial auto-correlation; the values are distributed so that central values show connections between low and high values. This means there is a clear spatial relationship, suggesting that the data are clustered. The value in one area reflects the value in neighboring areas. Specifically, the City of Zagreb and counties in the Pannonian and continental regions of Croatia have lower values compared to the mountainous and coastal counties, where agriculture is a strategic sector with a significant number of capacities for cultivation, storage, and processing of agricultural products.

Through the analyzed data and considering the laws of the Fifth Discipline, it can be concluded that current solutions are often ineffective and the result of non-systemic approaches. Initially, it is important to note that the analysis of spatial indicators presented in Table 1 shows that problems originate at the state level, primarily due to an inefficient legal system, inadequate legal protection, and the burden of government regulation, which poses significant risks for investors. Furthermore, some counties replicated models from more developed regions without carefully evaluating their spatial capacities and resources,

either due to the engagement of unqualified personnel or “ad hoc” solutions. This resulted in a weaker inflow of investments. Such problems are fundamentally linked to human behavior; due to incompetence, the approach to problem-solving often relied on “copy–paste” methods. Limited knowledge leads to serious consequences. Systemic thinking is highly challenging and requires visionary problem-solving to eliminate all negative implications and potential future problems at their root.

CONCLUSION

Agricultural production is a significant economic sector in the Republic of Croatia. This study presents the state of investments in agricultural facilities using an analysis of spatial planning indicators. At the national level, the results show that the weakest outcomes are in the areas of legal regulation, legal system efficiency, and the burden of government regulation, representing significant risks for investors. Conversely, the best position is observed in infrastructure quality, which provides a competitive advantage compared to other countries.

The correlation coefficient between total investments and investments in municipal infrastructure is 0.88, indicating a statistically significant positive correlation at the 0.05 significance level. With a test statistic value of 2.7764 (greater than zero), the null hypothesis (no significant correlation between land-use efficiency and investments) is rejected, and the alternative hypothesis (H1) is accepted.

The regression model shows that with 0 issued building permits, the expected investment volume is €2,777.4 thousand. An increase of €1,000 in volume of investment corresponds to an expected 1.7497 issued building permits for agricultural capacities. Multi-criteria decision-making for ranking investments spatially revealed the presence of spatial autocorrelation. Specifically, the City of Zagreb and counties in the Pannonian and continental regions have lower values compared to mountainous and coastal counties, where agriculture is a strategic sector with a high concentration of capacities for cultivation, storage, and processing of agricultural products.

Considering the Fifth Discipline laws, current solutions are often ineffective, a consequence of non-systemic decision-making, which aligns with the law that “today’s problems come from yesterday’s solutions.” Some counties copied models from more developed regions without carefully analyzing their spatial capacities, relying on unqualified staff and “copy-paste” solutions, which resulted in lower investment volumes, illustrating the law “faster is slower.”

Investing time and money in transforming spatial plans should include new methods for more efficient land use. While higher-quality planning increases immediate costs, the long-term benefits are significantly greater, as evidenced by the number of constructed facilities and increased business activity, aligning with the law “you can have your cake and eat it too, but not all at once.” A more careful approach to spatial planning ensures more functional use of land and its potential, reducing the likelihood that peripheral areas often owned by counties and municipalities become overgrown and abandoned. These areas can instead be transformed into business zones that generate financial revenue from rent and

business activity taxes, illustrating the law “dividing the elephant in half does not create two small elephants.”

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