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INTEGRATING WINE TOURSIM INTO GREEN AGRICULTURAL TRANSFORMATION: PATHWAYS TO SUSTAINABLE RURAL DEVELOPMENT IN SERBIA

Branislav Dudić[1], Elena Jovičić[2], Jelena Vujadinović[3], Alexandra Mittelman[4]

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ABSTRACT

This paper examines structural changes in Serbian agriculture and explores wine tourism's potential contribution to green transformation and rural development. Using data from the World Bank, FAO, Eurostat, and Serbia's Statistical Office for the period 2013–2023 (2024 where available), it examines key indicators of structural change, including agricultural value added, employment, productivity, and sectoral governmental expenditure, specifically the Agriculture Orientation Index (AOI). Results indicate that agriculture, forestry, and fisheries declined from 6.3% to 3.1% of GDP, reflecting structural change, while productivity growth remained uneven and vulnerable to shocks. Conversely, the wine sector witnessed an output increase of over 170%, followed by rising yields and enhanced vineyard management. Tourism also expanded, indicating increasing synergies between viticulture and tourism. The paper argues that wine tourism can support rural diversification and value creation, and recommends agricultural modernization, improved rural infrastructure, and integrated wine-tourism development in line with EU sustainability objectives.

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Introduction

The increasingly visible effects of climate change and the growing scarcity of natural resources highlight the necessity of applying the principles of sustainable development in different sectors of society, particularly within agriculture (Kushawaha et al., 2021). Sustainable agriculture has become one of the central priorities in modern economic and environmental policy, emphasizing the need to balance food security, economic efficiency, and ecological protection. The European Union (EU) embeds these goals within the Common Agricultural Policy (CAP), which integrates economic, environmental, and social objectives to promote competitive and sustainable agricultural systems (Pe'Er et al., 2019; Homet et al., 2024). As a holistic approach, sustainable agriculture emphasizes responsible resource use, ecosystem protection, and resilience to environmental and economic shocks (Atapattu et al.,2025; Raman, 2024; Herman, 2024).

For countries like the Republic of Serbia, where agriculture is a vital source of employment, food security, and rural development (Stojanović, 2021), the shift towards sustainability is an essential aspect of broader green transformation efforts. Sustainable agriculture promotes soil protection, biodiversity preservation, and reduced pollution, while encouraging diversification and social inclusion in rural communities (Rai et al., 2023; Umesha et al., 2018). These dynamics present opportunities to enhance rural economies via multifunctionality and innovation-driven development models.

Wine tourism stands out as a rapidly expanding and high-value segment that directly contributes to sustainable rural development (Bisht & Rauthan, 2023). Its emphasis on local products, ecological responsibility, and cultural authenticity makes it particularly compatible with green transformation agendas (Guzel & Gromova, 2016; Woosnam et al., 2024). Serbia's rich viticultural heritage, favorable agroecological conditions, and growing interest in rural tourism establish a strong foundation for this integration. Recent studies underscore wine tourism as a strategic driver of diversification and long-term growth for wineries (Turčinović et al., 2025), aligning with national and EU sustainability goals.

The purpose of this paper is to examine how Serbia's agricultural sector is transforming in the context of green development, with a particular focus on the wine sector and the potential of wine tourism as a mechanism for sustainable rural development. By combining macroeconomic indicators of agricultural performance with sector-specific data on viticulture and tourism, the paper aims to identify key trends, structural challenges, and development opportunities relevant in the context of Serbia's agricultural modernization and its alignment with EU agricultural policies.

In line with this objective, the paper addresses the following research questions:

(1) How has the agricultural sector in Serbia structurally transformed over the past decade in terms of value added, employment, productivity, and public support?

(2) What role does the wine sector play within this broader agricultural transformation, particularly in terms of value creation and modernization?

(3) To what extent does wine tourism represent a potential mechanism for sustainable rural development and diversification in Serbia?

Literature review

In the modern world, sustainability has become an essential and strategic issue for every kind of business (Kolte et al.,2022). Food production, a fundamental necessity for all living organisms, is directly connected to agriculture, which has a central role in supplying the diverse range of foods consumed daily, including cereals, legumes, grains, fruits, vegetables and livestock (Saikia & Laisharam, 2023). Conventional agricultural systems, characterized by intensive chemical inputs, mechanization, and hybrid seed use (Perković et al., 2017), have led to environmental degradation and greenhouse gas emissions (Praća et al., 2017). These challenges have driven the shift toward ecological and organic production models that prioritize environmental responsibility and enduring sustainability.

Sustainable agriculture is increasingly recognized as a crucial pathway for fulfilling the goals of Agenda 2030 (Hurduzeu et al., 2022) and the EU Green Deal (Wrzaszcz & Prandecki, 2020). Definitions typically underscore environmental conservation, resource efficiency, and the economic and social viability of farms (Sharma & Bipana, 2024; Sow & Debnath, 2023). This approach integrates ecological principles with technological innovation to mitigate environmental consequences and bolster system resilience (Tahat et al., 2020; Aničić et al., 2019). Wang et al. (2025) highlighted that, despite considerable challenges, the transition toward sustainable agriculture offers significant opportunities, which can be realized through effective collaboration among governments, stakeholders, and the global community.

The process of green transformation of agriculture includes the transition from traditional production models to those based on innovation, digitalization and renewable energy sources (Li & Guan, 2023). The need for innovation in agriculture is not only an imperative, but also a strategic approach to increase agricultural productivity and the agricultural economy in order to solve a critical problem (Stræte et al., 2022). Promoting the green transformation of agriculture represents an effective strategy to address challenges related to resource management, environmental sustainability, and rural development. However, existing literature offers limited insights into the internal mechanisms and pathways for achieving green transformation (Li et al., 2024). Boix-Fayos & De Vente (2023) highlighted several commonly reported challenges to attain sustainable food systems, including reduced crop yields, rising land demand, nitrogen needs, changes in diet, food waste, distribution and access to food, and externalities to third countries. Jurjević et al. (2019) emphasize that technological modernization, including precision agriculture, GIS systems, and digital management tools, can improve yields and reduce environmental impact. However, Serbia lags behind EU countries in digital adoption, due largely to limited financial resources and low digital literacy among farmers (Jurjević et al., 2019), but it can be improved by ensuring reliable access to modern communication technologies, strengthening technological

resources, and promoting awareness, developing skills and training human resources in rural areas (Zečević Stanojević et al., 2024).

Tourism significantly contributes to rural development by leveraging diverse natural and cultural resources (Ivona, 2021). Agritourism strengthens links between farmers and visitors, creating new income opportunities (Ferreira & Martín, 2020). Wine tourism, in particular, has rapidly expanded as a segment that supports rural diversification, cultural preservation, and environmental protection (Jezierska-Thöle et al., 2025). Its integration with agricultural production enhances sustainable destination models by promoting heritage, biodiversity, and local economic development (Bresciani et al., 2016; Andrade-Suárez & Caamaño-Franco, 2020).

Many studies highlight wine tourism's capacity to enhance environmental performance, stimulate innovation, and strengthen regional competitiveness (García Revilla & Martínez Moure, 2021; Martínez-Falcó et al., 2024a), arguing that wine tourism can support regenerative agriculture and circular economy principles (Martínez-Falcó et al., 2024b), though the benefits depend on stakeholder collaboration and careful environmental management (Pearson et al., 2024). Digitalization has further influenced the sector, particularly in the post-pandemic context (Festa et al., 2023).

Serbia has a long-standing agricultural tradition, with most of its rural population actively engaged in farming (Trlaković et al., 2021). According to the Republic Statistical Office, the country is home to approximately 508,325 agricultural holdings, reflecting the significant role that agriculture continues to play in rural livelihoods, food production, and the national economy (Republic Statistical Office, 2023). In this context, the development of wine tourism represents an opportunity for the integration of sustainable agriculture and rural transformation, thus opening up space for green modernization of the countryside and a more competitive position of the country. Wine tourism in Serbia has a long-standing tradition of more than 120 years (Maksimović et al., 2021). Today, Serbia boasts a substantial number of wineries with the potential to develop wine tourism and hosts numerous wine-focused events, reflecting the country's rich viticultural tradition. However, the structure of wine tourists has changed significantly, with wineries and wine events now mostly visited by wine lovers, while professional visitors constitute a much smaller number (Tomić et al., 2017). Aničić et al. (2019) emphasize the necessity to revitalize the cooperative system and strengthen various forms of collaboration among agricultural producers, along with increasing support for small family farms, following the models established in developed EU countries.

Materials and methods

This research integrates macroeconomic and sectoral data, covering the period 2013-2023 (or 2024 where available). Core agricultural indicators, such as agriculture value added (% GDP), agricultural employment (% total employment), and agricultural value-added growth, were derived from the World Bank's World Development Indicators. Data on agricultural and total government expenditure was sourced from FAO (2024)

and used to compute the Agriculture Orientation Index (AOI) following FAO/SDG 2.a.1 methodology:

AOI = (Agricultural value added/GDP) ÷ (Agricultural expenditure/Total expenditure)

Values exceeding one indicate that agriculture is accorded a greater policy priority in comparison to its economic contribution, whilst values below one suggest relative underinvestment. AOI for Serbia was taken directly from the World Bank SDG database, while AOI for the European Union was calculated using FAO COFOG agricultural expenditure and WDI agricultural value-added data. However, despite both datasets adhering to the same SDG methodology, slight disparities may arise from variations in data coverage, aggregation, and harmonization.

National-level statistical data were supplied by the Statistical Office of the Republic of Serbia (2024), which includes total agricultural output, crop and wine production, vineyard area, yield per hectare, and tourism statistics, such as the number of tourist arrivals and overnight stays. Agricultural output and wine production originally reported in RSD were converted to EUR using average annual exchange rates provided by the National Bank of Serbia (Table 1).

Table 1. Average annual exchange rate EUR/RSD

	2013	2014	2015	2016	2017	2018	2019	2020	2021	2022	2023	2024
EUR/ RSD	113.1	117.2	120.8	123.1	121.3	118.3	117.9	117.6	117.6	117.5	117.3	117.1

Source: NBS (2024)

The analysis employs descriptive and comparative statistical methods to investigate long-term structural dynamics in Serbian agriculture. Trends, growth rates, and structural ratios are examined to identify changes in agricultural performance, while figures and tables illustrate the correlations between agricultural output, wine production, and tourism development. This methodological approach enables a structured assessment of macro- and sector-level patterns relevant to green agricultural transformation and rural development in Serbia.

The study adopts a descriptive and exploratory perspective, focusing on the identification of long-term structural trends rather than on establishing causal relationships. Although the analysis is policy-oriented, it does not seek to estimate causal effects between agriculture, viticulture, and tourism, but instead examines their co-evolution over time at the national and sectoral levels. Accordingly, the findings should be interpreted as indicative of structural patterns and development potentials, rather than as evidence of direct policy impacts.

Within this framework, green agricultural transformation is interpreted in empirical terms as a structural process reflected through changes in economic contribution, employment dynamics, public support orientation, productivity trends, and the development of higher value-added and multifunctional activities. Given macro-level

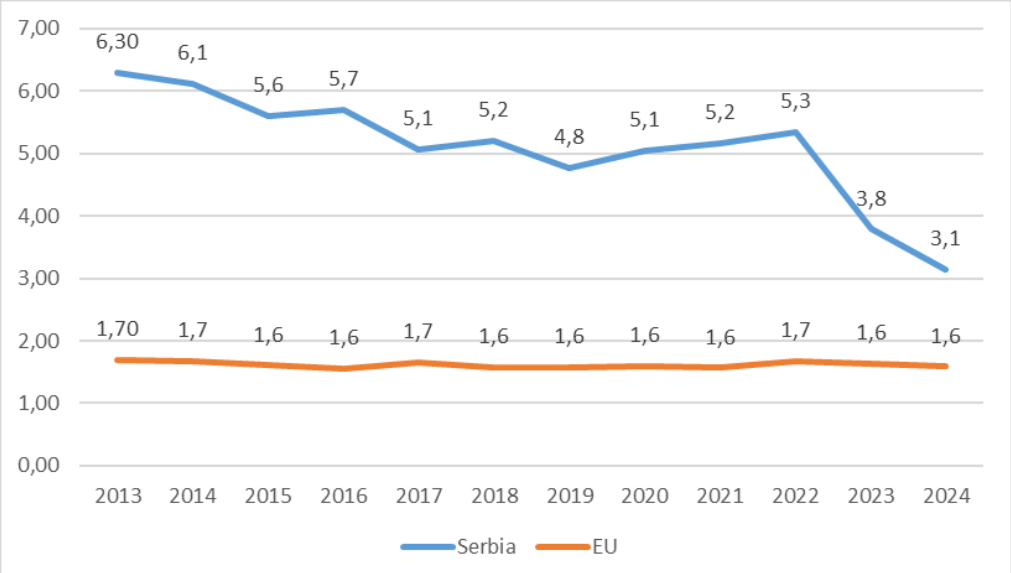
data constraints, the concept is assessed through a set of complementary indicators capturing economic, structural, and sectoral dimensions rather than through a single synthetic measure. This approach is consistent with applied policy-oriented research on agricultural transformation in transition and EU candidate countries, where gradual structural change and diversification are central analytical perspectives.

Results and Discussion

Structural Changes in Serbian Agriculture in Comparative Perspective

The results indicate a continuous decline in the contribution of agriculture, forestry, and fishing to Serbia's GDP (from 6.3% to 3.1%) over the observed period (Figure 1). While agriculture remains structurally important, its relative economic weight has diminished, reflecting broader processes of structural transformation typical of transition economies. This trend is consistent with patterns observed in EU member states, where agricultural value added has steadily decreased as economies diversify toward services and higher value-added activities (Pe'er et al., 2019).

Figure 1. Agriculture, forestry, and fishing, value added (% of GDP)



Source: Authors

However, the Serbian trajectory differs in pace and structure. Unlike the EU, where declining agricultural shares are accompanied by strong productivity growth and technological upgrading, Serbia's reduction in agricultural GDP contribution occurs alongside persistently high agricultural employment (see Figure 3). Similar mismatches between employment and value added have been identified in other Western Balkan and Southeast European countries, where structural adjustment remains incomplete and agriculture continues to absorb surplus labor (Aničić et al., 2019; Trlaković et al., 2021). This suggests that Serbia's agricultural transformation is still largely extensive

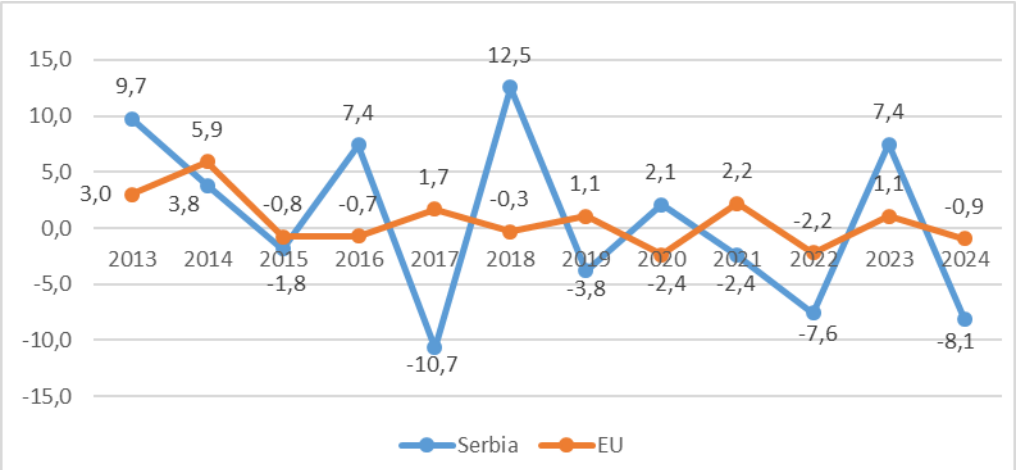
rather than productivity-driven, underscoring the necessity for a more focused strategy regarding investment and technical modernization.

From a sustainability perspective, this structural pattern limits Serbia's capacity to respond effectively to climate change and market shocks. Contemporary sustainable agriculture frameworks emphasize productivity improvements through innovation, resource efficiency, and diversification, rather than reliance on labor absorption as an adjustment mechanism (Hurduzeu et al., 2022; Sharma & Bipana, 2024). The Serbian case therefore illustrates a partial and uneven transition, where structural change is occurring without sufficient qualitative upgrading.

Volatility of Agricultural Growth and Climate Vulnerability

Agricultural value-added growth in Serbia exhibits pronounced volatility, with sharp contractions followed by strong recovery years (Figure 2). This contrasts with the relatively stable growth patterns observed in the EU, where policy instruments under the Common Agricultural Policy (CAP) play a stabilizing role through income support, risk-management tools, and rural development measures (Pe'er et al., 2019).

Figure 2. Agriculture, forestry, and fishing, value added (annual % growth)



Source: Authors

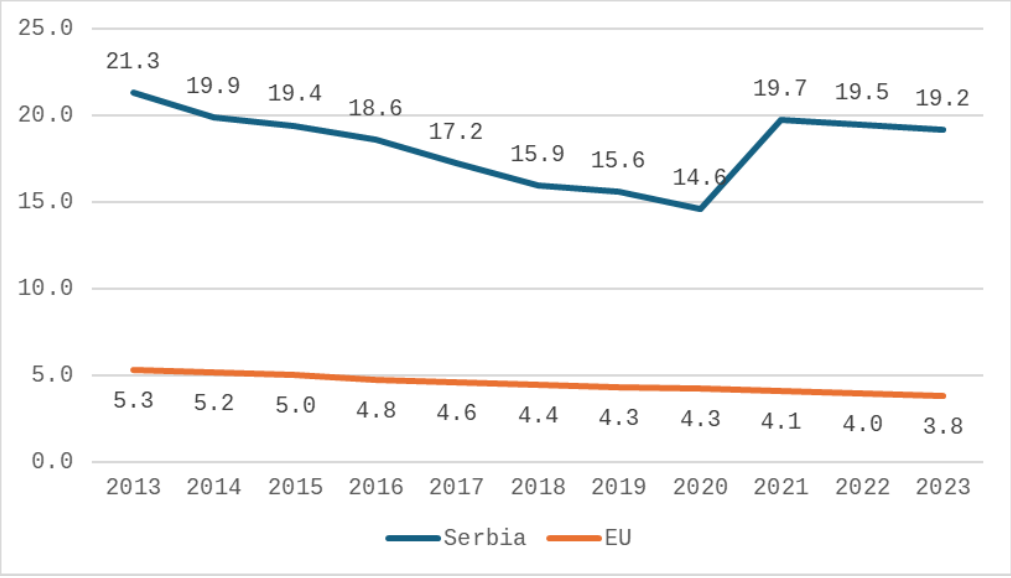
The observed volatility in Serbia is consistent with findings from studies on transition and emerging agricultural economies, which identify strong climate exposure, a production structure dominated by primary crop activities, and broader structural constraints as key drivers of instability (Praća et al., 2017; Jurjević et al., 2019; Županić et al., 2021). Additional research highlights low productivity levels and limited modernization as persistent challenges that further constrain adaptive capacity in such systems (Aničić et al., 2019). As a result, agricultural yields remain highly sensitive to weather conditions, while technological and structural limitations reduce the sector's ability to respond to external shocks.

Compared with countries that have advanced further in green agricultural transformation, such as newer EU member states that have absorbed CAP funds for modernization (OECD 2022; Matthews 2018), Serbia displays weaker resilience mechanisms. Li and Guan (2023) emphasize that green transformation requires not only environmental orientation but also investment in innovation, digitalization, and climate-smart technologies. The Serbian results confirm that without such investments, sustainability goals remain vulnerable to external shocks.

Employment Structure and Productivity Gaps

Despite a gradual decline, agricultural employment in Serbia remains significantly higher than the EU average (Figure 3). While the EU has experienced parallel declines in agricultural employment and value added, indicating productivity-led transformation, Serbia shows a persistent decoupling between labor input and economic output.

Figure 3. Employment in agriculture (% of total employment) (modeled ILO estimate)



Source: Authors

This pattern reflects what Aničić et al. (2019) describe as structural duality, referring to the coexistence of relatively more modernized and market-oriented segments alongside traditional small-scale farming characterized by low productivity. Similar dynamics have been documented in other transition economies, where limited access to capital, technology, and knowledge constrains structural adjustment processes and slows the transformation of agricultural labor structures (Jurjević et al., 2019; Zečević Stanojević et al., 2024).

From a policy standpoint, maintaining high agricultural employment without corresponding productivity growth poses long-term sustainability challenges. Sustainable agriculture frameworks stress that social sustainability should be achieved

through income diversification and value creation, not through the preservation of low-productivity employment.

Public Support and the Agriculture Orientation Index

An alternative viewpoint on Serbia's agricultural development can be derived from the Agriculture Orientation Index (AOI), which assesses the degree to which public expenditure aligns with the sector's contribution to the national economy. The AOI is defined as the ratio of government expenditure on agriculture, forestry, and fishery to the agriculture value added share of GDP. A value of one indicates balanced prioritization, but value below one denotes underinvestment in relation to the sector's economic significance.

Table 2. The agriculture orientation index for government expenditures

	2013	**2014**	**2015**	**2016**	**2017**	**2018**	**2019**	**2020**	**2021**	**2022**	**2023**
Serbia	0.29	0.31	0.32	0.31	0.37	0.34	0.40	0.33	0.32	0.37	0.67
EU*	0.35	0.36	0.36	0.34	0.33	0.35	0.35	0.35	0.34	0.34	0.36

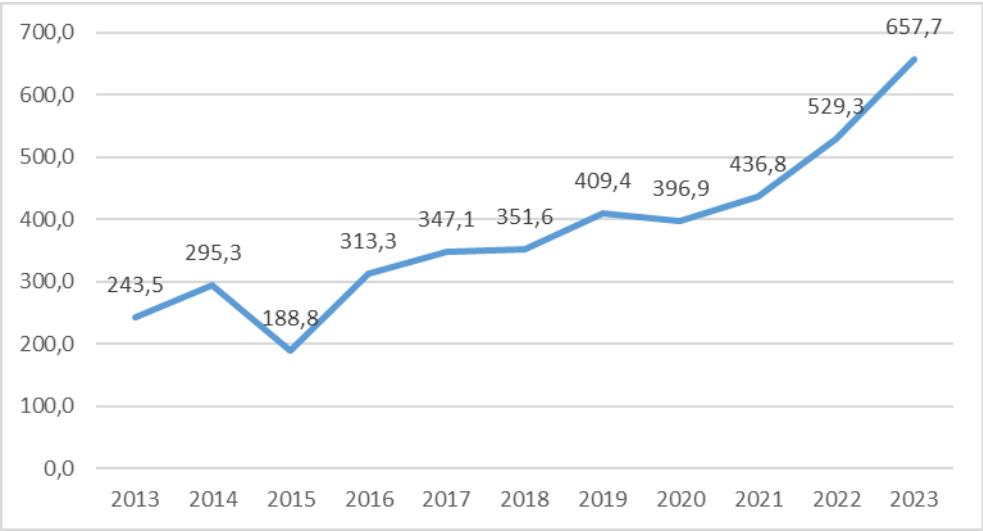
Source: World Bank data360; *authors based on the FAO database.

Between 2013 and 2023, the average agriculture Output Index (AOI) for the European Union was approximately 0.35, showing that agriculture expenditure constitutes about one-third of the sector's contribution to GDP. Although this may indicate underinvestment from a purely proportionate viewpoint, it actually demonstrates a mature, high-efficiency system where agricultural and rural support is facilitated through multifunctional CAP instruments, which means that funds can also be distributed indirectly (via rural development, environmental schemes, and structural instruments) (Pe'er et al., 2019; Wrzaszcz & Prandecki, 2020). Conversely, Serbia's AOI fluctuated between 0.25 and 0.40 during most of the decade, indicating a limited governmental focus on agriculture. However, a significant rise to about 0.7 in 2023 implies a strategic move towards enhanced prioritizing. This may indicate improvement in the process of alignment with EU standards and harmonizing its agricultural expenditure frameworks with EU protocols, especially via IPARD and Green Transition initiatives.

Dynamics of Wine Production and Viticulture

Although total agricultural output grew by roughly 36% throughout the decade, wine production surged by nearly 170%, rising from EUR 243.5 million in 2013 to EUR 657.7 million in 2023 (Figure 4). This growth rate significantly surpasses that of the total agricultural sector, indicating heightened market demand and structural enhancement within Serbian viticulture. Although vineyard area decreased moderately from approximately 21,000 hectares in 2013 to 17,700 hectares in 2023, the yield per hectare increased from 5.8 to 7.3 tons, indicating transition towards more intense and technologically sophisticated production systems, supported by expenditures in vineyard revitalization and quality enhancement.

Figure 4. Annual wine production (EUR million)



Source: Authors

Serbia's wine production dynamics are consistent with global trends in emerging and premium wine regions, where modernization focuses on quality upgrading rather than area expansion (García Revilla & Martínez Moure, 2021). Also, compared to traditional bulk-oriented agricultural production, viticulture exhibits stronger compatibility with sustainability principles, particularly through differentiation strategies, territorial embeddedness, and value upgrading (Bresciani et al., 2016; Andrade-Suárez & Caamaño-Franco, 2020).

Recent studies show that the integration of wine tourism and sustainability-oriented practices is associated with improvements in economic performance, environmental management, and social outcomes in wine-producing regions (Martínez-Falcó et al., 2024a; 2024b). Serbia's results align with these findings, suggesting that viticulture can act as a catalyst for green agricultural transformation when linked to tourism and local value chains.

Tourism Growth and Synergies with Agriculture - Integrating Wine Tourism into Green Transformation

The dynamics of tourism in Serbia over the last decade have reflected the structural changes seen in agriculture and viticulture. From 2013 to 2024, total tourist visits more than quadrupled, rising from 2.2 million to 4.4 million, while the number of foreign visitors surged by 158%. Overnight stays exhibited a comparable trend, increasing from 6.6 million to 12.7 million (Figure 5). Following a brief downturn in 2020 attributed to the COVID-19 pandemic, tourism saw a robust resurgence, propelled by domestic demand and the increasing appeal of specialized sectors such as gastronomy and wine tourism.

Figure 5. Tourists' arrivals and tourists' nights spent in Serbia, 2013-2024



Source: Authors

Within this context, the wine sector exhibits characteristics that are compatible with the principles of green transformation, particularly through its orientation toward higher value-added production, more efficient resource use, and the preservation of cultural and landscape heritage (Bisht & Rauthan, 2023; Guzel & Gromova, 2016). The integration of viticulture into tourism activities enhances agricultural multifunctionality, as vineyards simultaneously function as production units, cultural assets, and elements of the rural environment. This approach is consistent with broader rural development strategies promoted by the EU and the OECD, which emphasize diversification of rural economies, non-farm income generation, environmental sustainability, and social cohesion (OECD, 2022; European Parliament, 2022).

The parallel growth of tourism and wine production in Serbia suggests the emergence of synergies between viticulture and rural tourism. This observation aligns with existing research that identifies wine tourism as a complementary mechanism for rural development, capable of fostering economic diversification, strengthening territorial identity, and increasing local value creation (Andrade-Suárez & Caamaño-Franco, 2020; Jezierska-Thöle et al., 2025). At the same time, the literature cautions that the sustainability impacts of wine tourism depend heavily on supportive institutional frameworks, adequate infrastructure, and effective coordination among stakeholders (Pearson et al., 2024; Turčinović et al., 2025). In this respect, Serbia's experience is comparable to that of other transition economies, where wine tourism represents a promising yet still unevenly developed pathway for rural diversification.

Compared with established EU wine regions, Serbia remains at an earlier stage of institutional and infrastructural development. Nevertheless, the existence of organized wine routes and increasing entrepreneurial activity indicates a gradual movement toward development patterns observed in European models of sustainable rural tourism (Jezierska-Thöle et al., 2025; Maksimović et al., 2021). Illustrative examples, such as wine routes in Fruška Gora, Šumadija, and the Negotinska Krajina, demonstrate how wineries can generate additional value through tasting rooms, small-scale accommodation, local gastronomy, and cultural events, thereby contributing to the formation of a more integrated wine tourism ecosystem. In line with existing research (Bresciani et al., 2016; Sow & Debnath, 2023), the Serbian case underscores the importance of diversification and multifunctionality as key pathways toward green and sustainable rural development.

Taken together, the results highlight the interconnected nature of agricultural transformation, sectoral differentiation, and tourism development in Serbia. While traditional agriculture continues to face structural challenges and volatility, the wine sector illustrates how targeted modernization and value upgrading can enhance resilience. The parallel expansion of tourism, particularly wine tourism, further reinforces the role of multifunctionality as a linking mechanism between agriculture and rural development, suggesting that integrated sectoral approaches are essential for advancing green and sustainable rural transformation.

Conclusion

The results of the study affirm that the agricultural sector of Serbia is experiencing steady but uneven transformation, which is characterized by decreasing GDP contribution, consistently high agricultural employment and significant fluctuations in value-added growth. These patterns indicate that a sector is still hindered by technological lag, climate vulnerability, and limited diversification. At the same time, the Agriculture Orientation Index shows historically low but recently improving levels of public support, suggesting a potential alignment with EU agriculture policy frameworks.

In contrast to broader agricultural stagnation, the wine sector indicates a notable trend of modernization. Wine output increased significantly despite a reduction in vineyard area, demonstrating improvements in yield and quality. These structural changes reflect global trends in premium wine regions and correspond with EU sustainability and rural diversification goals. Furthermore, the rapid growth of tourism fosters synergy between viticulture, rural hospitality, gastronomy, and cultural heritage, thereby enhancing local economies through multifunctionality.

From a policy perspective, these findings emphasize the significance of leveraging high-value, culturally ingrained sectors, such as viticulture and wine tourism, to accelerate Serbia's green agricultural transformation. This approach is consistent with the Common Agricultural Policy's focus on smart specialization, environmental protection, and rural economic diversification. Enhancing the regulatory framework

for wine tourism, expanding IPARD funding, and improving local value chains would allow Serbia to maximize the economic, social, and environmental benefits of this development path.

To realize the potential adequately, the following policy recommendations are proposed:

- Harmonize national agriculture and rural development strategies with the EU Green Deal and CAP – Serbia should enhance its policy alignment with the Common Agricultural Policy (CAP 2023–2027) by integrating sustainability criteria, climate adaptation strategies, and biodiversity protection into all agricultural support programs, with a stronger emphasis on CAP Pillar II priorities.
- Increase investment in agricultural modernization and climate resilience – Strategic investments in irrigation systems, climate-smart technology, crop insurance programs, early warning systems, and mechanization are crucial for mitigating volatility in agricultural production.
- Enhance institutional and financial support for the wine sector – The recent rise in agricultural expenditure should be accompanied by better targeting and transparency. Funding should prioritize value-added chains, eco-certification, sustainability standards, and digital tools for vineyard and winery management.
- Integrate wine tourism into national and regional rural development strategies – A coordinated framework connecting agriculture, tourism, and cultural heritage would enhance policy coherence and promote the development of integrated rural products. This alignment would promote sustainable revenue diversification and enhance Serbia's position in the regional wine tourism market.
- Develop integrated wine and rural tourism clusters – Corridors such as Fruška Gora, Šumadija, and Negotinska Krajina should combine vineyard modernization, hospitality, gastronomy, and heritage. These clusters can follow EU initiatives such as such as the CAP 2023–2027's Smart Villages strategy (supporting digital and social innovation in rural areas) and the EAFRD under the CAP, providing rural development funding for diversification and sustainability.
- Promote green innovation and certification in viticulture – Enhancing access to renewable energy technologies (e.g., solar-powered wineries, water recycling systems) and advocating for organic and low-emission viticulture would allow better alignment of Serbian producers with EU sustainability criteria. The introduction of eco-labels and Protected Geographical Indication (PGI/PDO) certification should be encouraged to enhance export competitiveness and customer confidence.
- Enhance institutional and governance capacity – Creating specialized inter-ministerial coordination frameworks among the Ministries of Agriculture, Tourism, and Environmental Protection would improve strategic planning and the coherence of rural development initiatives. This coordination is crucial for

improving access to EU funds and enabling local authorities to develop and implement integrated development projects.

- Invest in human capital and the transfer of knowledge – The shift towards sustainable and innovation-driven agriculture and tourism requires new skills. Training programs in sustainable viticulture, agrotourism management, digital marketing, and circular economy principles should be developed in cooperation with universities and vocational schools. Cooperation with EU educational networks, such as Erasmus+ for Rural Innovation, can further foster this process.

Overall, Serbia's progress toward green transformation will depend on the integration of policy tools, access to EU funds, and effective coordination across sectors. The wine sector represents a concrete success narrative, highlighting how modernization, cultural legacy, and ecological awareness can converge into a sustainable development paradigm. By aligning national objectives and strategies with EU regulations, Serbia can strengthen its agricultural sector, improve environmental management, and establish itself as a competitive and sustainable wine and tourism destination in the Western Balkans.

Limitations and Future Research Directions

This study is predominantly descriptive and relies on secondary data, which may contain discrepancies in coverage, indicator definitions, and reporting methodology. In addition, the analysis is conducted at the macro and sectoral level and does not capture micro-level dynamics related to individual farms, wineries, or tourist behavior. Consequently, the findings should be interpreted as indicative of structural trends and policy-relevant linkages rather than firm-level or consumer-level impacts. Regional differences within Serbia are inadequately represented, potentially obscuring variations in agricultural productivity and the advancement of wine tourism. Future research should integrate regional datasets, geographical analysis, and econometric models to investigate localized development patterns. While the Agriculture Orientation Index provides insights into policy prioritization, it does not assess the qualitative effectiveness of public spending. Thus, complementary indicators for green investment and sustainability outcomes should be established. Ultimately, the relationship between wine tourism and rural sustainability requires deeper investigation using field surveys, stakeholder interviews, and case studies to better understand stakeholder behavior, governance challenges, and green transition pathways at the local level.

Conflict of interests

The authors declare no conflict of interest.

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DIGITAL LITERACY AND READINESS FOR DIGITAL TRANSFORMATION IN SERBIAN AGRICULTURE

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ABSTRACT

Digital transformation plays an increasingly important role in improving productivity and competitiveness in agriculture. This study analyzes the level of digital literacy and readiness for digital transformation among farmers in the Republic of Serbia from an economic and information-technology perspective. A quantitative exploratory approach was applied using survey data collected through face-to-face interviews with 170 agricultural producers who voluntarily participated in the study. The results show frequent use of basic digital tools, particularly mobile applications and online sales, while advanced technologies such as sensor systems are rarely adopted. Multiple linear regression did not identify a statistically significant relationship between the selected indicators of digital literacy and farmers' overall readiness for digital transformation. Descriptive findings indicate that lack of knowledge represents the main perceived barrier to digitalization, while training and competency development are identified as important priorities for further digital development. The findings highlight the need for targeted training programs and supportive measures aimed at facilitating the further digitalization of Serbian agriculture.

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Introduction

Digital transformation is increasingly reshaping agricultural production by enabling more efficient resource management, improved decision-making, reduced operating costs, and better access to markets. Digital technologies such as mobile applications, sensor systems, the Internet of Things (IoT), and data-driven solutions can contribute to productivity and competitiveness. However, their effective adoption depends not only on technological availability but also on farmers' knowledge, skills, and readiness to integrate digital tools into agricultural activities. Digital literacy is therefore an important aspect of agricultural digitalization. Farmers with limited digital knowledge and skills may face difficulties in adopting and effectively using digital technologies, even when such technologies are available. This challenge is particularly relevant in transition economies such as Serbia, where agricultural digitalization is characterized by uneven technology adoption, financial constraints, infrastructure limitations, and differences in farmers' digital competencies. Accordingly, this study examines the level of digital literacy and readiness for digital transformation among farmers in the Republic of Serbia. Particular attention is given to the use of digital technologies, perceived benefits and barriers to digitalization, and farmers' priorities for future digital development. The study aims to provide empirical evidence that may contribute to a better understanding of digital transformation in Serbian agriculture and support the development of appropriate training, policy, and institutional measures.

Literature Review

Digital transformation in agriculture involves the integration of digital technologies into production, management, and decision-making processes. Within the broader development of Agriculture 4.0, technologies such as sensors, mobile applications, the Internet of Things (IoT), artificial intelligence, and data-driven systems can support more precise monitoring, resource management, and agricultural productivity (Kara et al., 2023). However, the benefits of agricultural digitalization depend not only on the availability of technologies but also on farmers' capacity to understand, adopt, and effectively use them. This makes farmers' digital competencies and readiness for technology adoption important dimensions of agricultural digital transformation. Previous studies show that digital technologies can contribute to agricultural productivity, operational efficiency, and more sustainable resource management (Subeesh & Mehta, 2021; Javaid et al., 2022). Nevertheless, digitalization also introduces barriers related to implementation costs, data management, cybersecurity, regulatory requirements, and the complexity of advanced technologies (Osinga et al., 2022). These findings indicate that agricultural digitalization should be examined not only from the perspective of technological benefits, but also in terms of the barriers that may affect farmers' ability and willingness to adopt digital solutions.

The primary challenge for high-technology agriculture lies in ensuring that new technologies help farmers become more economically competitive (Jurjević et al., 2019).

Effective adoption of smart agriculture requires not only technological infrastructure but also information-intensive and knowledge-based competencies (Milovanović, 2014). IoT and mobile technologies can support agricultural monitoring and decision-making (Gondchawar & Kawitkar, 2016), while ICT provides farmers with more timely access to relevant information (Mahant et al., 2012). These studies indicate that farmers' knowledge and ability to use digital information represent important conditions for translating technological availability into practical agricultural benefits.

From an economic perspective, digital technologies may reduce labor and information costs, improve resource utilization, facilitate access to markets, and strengthen farm competitiveness (Mykulskyi, 2019; Jurjević et al., 2019; Jia, 2024). Digital solutions may also support production planning and decision-making by providing timely information relevant to agricultural activities (Fuentes-Peñailillo et al., 2024). However, farmers' perceptions of these benefits are particularly important because perceived usefulness may influence their willingness to use and further adopt digital technologies.

At the policy level, digital agriculture is recognized as an important component of the development of resilient and sustainable agri-food systems, with technology, innovation, and data identified as important accelerators of agricultural development (FAO, 2021). Nevertheless, the growing technological potential of digital agriculture does not automatically imply successful adoption at the farm level. The human dimension—particularly farmers' knowledge, digital competencies, perceptions, and readiness to use available technologies—therefore requires greater attention.

Although previous research has extensively examined the technological potential of digital agriculture, the successful implementation of digital technologies also depends on farmers' ability to understand, adopt, and effectively use these technologies. Existing studies indicate that digital solutions can improve access to information, support decision-making, optimize agricultural activities, and increase productivity (Mahant et al., 2012; Jha et al., 2019; Charania & Li, 2019). However, technological availability alone does not ensure successful digital transformation. Farmers' knowledge and ability to integrate digital tools into everyday agricultural activities remain important conditions for effective adoption. In this context, examining digital literacy together with readiness for digital transformation provides an important user-centered perspective that complements predominantly technology-oriented studies. This is particularly relevant in the Serbian agricultural context, which remains insufficiently examined in the literature reviewed in this study. Accordingly, the following hypothesis is proposed:

H1: There is a statistically significant relationship between the level of farmers' digital literacy and their readiness for the digital transformation of agricultural holdings.

Use of digital technologies and perceived benefits of digitalization

Previous studies emphasize that the application of digital technologies can improve resource utilization, reduce labor requirements, facilitate access to information and markets, and strengthen the competitiveness of agricultural producers (Mykulskyi,

2019; Jurjević et al., 2019; Jia, 2024). Digital tools can also support more efficient production planning and decision-making through access to real-time information and data (Mahant et al., 2012; Fuentes-Peñailillo et al., 2024). These findings suggest that farmers who use digital technologies more frequently may have greater direct experience with their economic and operational benefits and may therefore evaluate the benefits of digitalization more positively. Based on this reasoning, the following hypothesis is proposed:

H2: More frequent use of digital technologies in agricultural production and business operations is associated with more positive farmers' perceptions of the benefits of digitalization.

Knowledge and institutional barriers to digitalization

The literature also demonstrates that the adoption of advanced technologies in agriculture involves numerous challenges. Previous studies identify implementation costs, data management, cybersecurity, regulatory requirements, and the complexity of digital technologies as important constraints (Osinga et al., 2022; Amorim et al., 2021). At the same time, effective smart agriculture requires information-intensive and knowledge-based competencies, indicating that farmers' knowledge and skills constitute an important condition for successful technology adoption (Milovanović, 2014; Gondchawar & Kawitkar, 2016). These different categories of barriers justify examining whether farmers perceive insufficient knowledge as a more important obstacle than legal and institutional constraints. Accordingly, the following hypothesis is proposed:

H3: A lack of knowledge represents a more significant barrier to the adoption of digitalization than legal and institutional constraints among farmers in the Republic of Serbia.

Materials and methods

This study is designed as a quantitative, exploratory research aimed at examining the level of digital literacy and readiness for digital transformation among farmers in the Republic of Serbia. The research focuses on farmers' perceptions, usage patterns, and attitudes toward digital technologies in agricultural production and business activities.

The subject of this research is the level of digital literacy and readiness for the digital transformation of agricultural holdings in the Republic of Serbia, with particular emphasis on the frequency and forms of digital technology adoption, barriers to the digitalization process, and priorities for further development.

The primary objective of the study is to determine the degree of digital literacy and readiness of farmers in Serbia for the introduction and broader adoption of digital technologies in agricultural production and business operations.

The secondary objectives of the study include:

- Analyzing the frequency and modes of digital technology use in agricultural holdings;
- Identifying key barriers in the process of agricultural digitalization;
- Examining the relationship between farmers' socio-demographic characteristics and their readiness for digital transformation;
- Identifying farmers' priorities for the upcoming period in the context of digital development (training, financing, and market access).

This quantitative exploratory research was conducted with the aim of determining the digital literacy and readiness for digital transformation of farmers in Serbia. The study was conducted from September to mid-December 2025. The initial sampling frame consisted of a list of 422 farmers obtained through local community offices (mesne zajednice) in the territory of the Republic of Serbia. Farmers from this list were contacted and invited to participate in the study. Participation was voluntary, and interviews were scheduled only with farmers who agreed to take part in the research. Consequently, the final sample consisted of 170 farmers who voluntarily participated in face-to-face interviews. Given this recruitment procedure, the sample should be considered a non-probability voluntary response sample rather than a random sample. Participation was anonymous, and prior to the interview, each participant provided informed consent for the use of the collected data for academic research purposes. The data analysis was performed with SPSS version 25 and JASP version 0.95. A survey was carried out involving 170 participants ($N = 170N = 170$). The questionnaire was divided into two separate sections. The initial section contained seven questions designed to collect vital demographic data, while the subsequent section featured 17 Likert-type research questions (see Table 1) and 7 closed-ended research questions, which pertained to the digital literacy and readiness of farmers.

Results

Table 1. Seventeen Likert-type ordinal variables from the questionnaire

No.		N		Mean	Std. Dev.	Min.	Max.
		Valid	Missing				
01	Digitalization increases my productivity	170	0	4.65	0.547	3	5
02	I rate my knowledge of digital technologies in agriculture as:	170	0	3.30	0.842	2	5
03	I believe that digital technologies contribute to sustainable agriculture	170	0	4.77	0.422	4	5
04	I have sufficient knowledge to use digital tools	170	0	2.45	0.522	2	4
05	Digitalization will improve market access	170	0	4.76	0.425	4	5
06	I use the internet daily for agriculture information	170	0	2.66	0.670	1	4
07	Digital technologies reduce my costs	170	0	3.58	0.928	2	5

No.		N		Mean	Std. Dev.	Min.	Max.
		Valid	Missing				
08	I am satisfied with the technical support provided by digital solution suppliers	170	0	3.20	0.735	2	5
09	I plan to expand the use of digital technologies in the next two years	170	0	4.72	0.449	4	5
10	Subsidies would motivate me to adopt more digital tools	170	0	4.98	0.132	4	5
11	I use digital methods for traceability	170	0	2.50	0.501	2	3
12	Digitalization helps reduce the use of pesticides	170	0	2.50	0.501	2	3
13	Digitalization contributes to the competitiveness of my farm	170	0	2.50	0.501	2	3
14	Digital technologies are too expensive for my farm	170	0	4.65	0.548	3	5
15	Poor internet infrastructure makes my work more difficult	170	0	4.77	0.422	4	5
16	I am concerned about data security	170	0	4.86	0.349	4	5
17	Overall readiness of my farm for digital transformation	170	0	3.13	0.456	2	4

Source: Authors' calculations

A total of 170 respondents completed the survey, of which 90 (53%) were female and 80 (47%) were male. In terms of age distribution, 16 respondents (9.4%) fell into the 18-30 age group, while the largest segment, 105 respondents (61.8%), belonged to the most economically active age group of 31-50 years. Additionally, 49 respondents (28.8%) were part of the oldest age group. The majority of respondents held a secondary vocational qualification, totaling 108 or 63.5%, while the remaining 62 respondents or 36.5% possessed a higher education qualification. All respondents own agricultural land. Of these, 133 or 78.2% reside in rural areas, while 37 or 21.8% live in suburban regions. The largest number of respondents, 117 (68.8%), have agricultural land measuring between 10.01 and 20 hectares. There are 33 respondents (19.4%) who are larger landowners with over 20 hectares, whereas the smallest group, consisting of 20 respondents (11.7%), has smaller plots ranging from 2 to 5 hectares. Regarding the frequency of sectors in which they are engaged (see Table 2), the sample predominantly includes livestock farmers, followed by organic producers and fruit growers, with the fewest being crop farmers.

Table 2. Frequencies for Production sector

Production sector	Frequency	Percent	Valid Percent	Cumulative Percent
Crop farming	25	14.706	14.706	14.706
Fruit growing	37	21.765	21.765	36.471
Livestock	72	42.353	42.353	78.824
Organic production	36	21.176	21.176	100.000
Missing	0	0.000		
Total	170	100.000		

Source: Authors' calculations

Descriptive statistics of the dataset

The following tables present a summary of descriptive statistics based on the results of closed-ended research questions on the phenomenon of literacy among Serbian farmers.

Table 3. Frequencies for Do you track income and expenses digitally?

Do you track income and expenses digitally?	Frequency	Percent	Valid Percent	Cumulative Percent
No	58	34.118	34.118	34.118
Yes	112	65.882	65.882	100.000
Missing	0	0.000		
Total	170	100.000		

Source: Authors' calculations

The results of the descriptive statistics indicate that the majority of respondents use digital tools to monitor income and expenditures. Specifically, 65.88% of respondents reported that they digitally track their finances, while 34.12% do not use digital methods in this area. This distribution of responses indicates that digital tools for monitoring income and expenditures are relatively widely used among the surveyed farmers. However, this finding alone should not be interpreted as evidence of a high level of financial literacy, as financial literacy was not directly measured in this study.

Table 4. Frequencies for Investments in modernization in the last 3 years (EUR)

Investments in modernization in the last 3 years (EUR)	Frequency	Percent	Valid Percent	Cumulative Percent
5001 - 20000 EUR	164	96.471	96.471	96.471
< 5000 EUR	4	2.353	2.353	98.824
> 20000 EUR	2	1.176	1.176	100.000
Missing	0	0.000		
Total	170	100.000		

Source: Authors' calculations

The data presented in Table 4 indicate that the predominant share of respondents (96.47%) invested between EUR 5,001 and EUR 20,000 in modernization over the past three years. A significantly smaller proportion of respondents invested less than EUR 5,000 (2.35%), while only 1.18% reported investments exceeding EUR 20,000. This distribution of results suggests that most respondents pursue moderate levels of investment in modernization, which may reflect a gradual and cautious approach to improving business processes, influenced by financial capacity and/or risk perception. The absence of missing data further confirms the validity and consistency of the collected information.

Table 5. Frequencies for Do you use credit for business operations?

Do you use credit for business operations?	Frequency	Percent	Valid Percent	Cumulative Percent
No	50	29.412	29.412	29.412
Yes	120	70.588	70.588	100.000
Missing	0	0.000		
Total	170	100.000		

Source: Authors' calculations

Table 5 shows that the majority of respondents (70.59%) use credit in their business operations, while 29.41% do not rely on credit financing. This result indicates a high dependence on external financial sources among farmers, suggesting that credit represents an important instrument for maintaining liquidity and supporting investments in agricultural production. The widespread use of credit also implies that access to financial resources may play a relevant role in enabling modernization and the adoption of digital technologies, which often require initial capital investments. The absence of missing data confirms the reliability of the findings and allows for consistent interpretation.

Table 6. Frequencies for I use the following technologies:

I use the following technologies:	Frequency	Percent	Valid Percent	Cumulative Percent
E-invoicing	31	18.235	18.235	18.235
Mobile applications	70	41.176	41.176	59.412
Online sales	54	31.765	31.765	91.176
Sensors	15	8.824	8.824	100.000
Missing	0	0.000		
Total	170	100.000		

Source: Authors' calculations

The results presented in Table 6 illustrate the structure of modern technology adoption among the respondents. Mobile applications are the most widely used technology, adopted by 41.17% of respondents, indicating a high level of acceptance of mobile digital solutions in everyday business operations. This is followed by online sales channels, used by 31.76% of respondents, confirming the growing importance of electronic commerce. E-invoicing is applied by 18.23% of respondents, while the use of sensor technologies is the least prevalent (8.82%), which may indicate the higher technical and financial complexity associated with these solutions. Overall, the results point to an uneven level of digital transformation, characterized by the predominant use of basic and moderately complex digital technologies.

Table 7. Frequencies for Frequency of using digital technologies

Frequency of using digital technologies	Frequency	Percent	Valid Percent	Cumulative Percent
Daily	103	60.588	60.588	60.588
Occasionally	67	39.412	39.412	100.000
Missing	0	0.000		
Total	170	100.000		

Source: Authors' calculations

Specifically, 60.59% of respondents (N = 103) reported using digital technologies on a daily basis, while 39.41% of respondents (N = 67) indicated that they use these technologies occasionally. The obtained results point to a relatively high frequency of digital technology usage among the respondents, confirming that digital solutions are to a significant extent integrated into their business activities. This response structure suggests the existence of a favorable environment for further digital transformation, while also highlighting the need for additional measures to encourage more intensive and continuous use of digital technologies among the segment of respondents who currently use them only occasionally.

Table 8. Frequencies for Main obstacles to introducing digitalization

Main obstacles to introducing digitalization	Frequency	Percent	Valid Percent	Cumulative Percent
Lack of knowledge	131	77.059	77.059	77.059
Legal obstacles	39	22.941	22.941	100.000
Missing	0	0.000		
Total	170	100.000		

Source: Authors' calculations

The analysis of the results presented in Table 8 indicates that a lack of knowledge represents the dominant barrier in the process of introducing digitalization. As many as 77.05% of respondents stated that insufficient knowledge and digital competencies constitute the key limiting factor, clearly highlighting the need for additional education, training programs, and advisory support. On the other hand, legal constraints were identified as the main barrier by 22.94% of respondents, suggesting that the regulatory framework, although important, has a considerably smaller impact compared to human and organizational factors. This structure of responses suggests that successful digital transformation may depend not only on institutional support but also on the development of knowledge, skills, and users' readiness to adopt new technologies.

Table 9. Frequencies for Most important priority for the next two years

Most important priority for the next two years	Frequency	Percent	Valid Percent	Cumulative Percent
Financing	53	31.176	31.176	31.176
Market	53	31.176	31.176	62.353
Training	64	37.647	37.647	100.000
Missing	0	0.000		
Total	170	100.000		

Source: Authors' calculations

The analysis of Table 9 shows that respondents most frequently identify training and knowledge enhancement as the most important priority for the next two years (37.64%), indicating a growing awareness of the importance of human capital development and continuous learning. Financing and market access rank second, with equal shares of responses (31.17% each), suggesting that these factors are recognized as important but less dominant compared to investments in knowledge and skills. Overall, the results indicate a shift in focus toward strengthening competencies as a foundation for long-term development and adaptation to contemporary business challenges. Accordingly, the findings reveal a high level of acceptance and daily use of digital technologies among respondents, with mobile applications and online sales emerging as the most frequently used digital tools. At the same time, a lack of knowledge is identified as the key barrier to further digitalization, while investment in training and competency development is recognized as the most important priority for the upcoming period, ahead of financing and market access.

Validation of the research scales

Before conducting the reliability analysis, the distribution of responses to the Likert-type items was examined. The descriptive results presented in Table 1 indicate a restricted range of responses across several items, suggesting limited variability in the data. Item 17 ("Overall readiness of my farm for digital transformation") was retained as a separate single-item indicator of overall readiness. Given the limited response variability and the exploratory nature of the study, the psychometric properties of the proposed scales were subsequently assessed before further statistical analysis. To assess the potential presence of common method bias in the Likert-type items, Harman's single-factor test was conducted. A principal axis factor analysis with one fixed factor indicated that a single factor explained 11.468% of the total variance, which is below the commonly used 50% threshold (Aguirre-Urreta & Hu, 2019). This result suggests that common method variance is unlikely to represent a dominant source of variance in the data. However, given the limitations of Harman's single-factor test, this finding should be interpreted with caution. We divided the research questions from the questionnaire into two research scales, a larger one with 13 variables that measured the positive aspects of digitalization in agriculture and a smaller one with 3 variables that measured the negative aspects of the aforementioned digitalization. In Table 1, the first 13 variables

refer to the positive scale, which we called the Digital Farmer (DF) Scale, while the next 3 variables make up the DF Obstacles scale. The first step in the analysis was to check the relationship between these two scales by conducting the Pearson product-moment correlation coefficient test. There was a positive, very weak and statistically insignificant correlation between the scales, $r = .126, n = 170, p = .110$. Although statistically insignificant, we were surprised by the positive sign of the correlation, as we expected a negative one. The next step in our analysis was to conduct a reliability study for our scales. The internal consistency of both scales was assessed as unacceptable, as values below .60 are considered unacceptable (Pallant, 2020). The 13-item DF scale recorded a Cronbach's alpha coefficient of .332. Furthermore, the 3-item Obstacles to DF scale even recorded a slightly negative coefficient of -.022. The negligible result automatically led to the discontinuation of the smaller-scale testing, while we decided to conduct a factor analysis on a larger scale. The 13 items of the DF Scale were subjected to further analysis through principal component analysis (PCA). This statistical technique is employed to decrease the dimensionality of a dataset that contains numerous interrelated variables while still retaining a significant amount of variance. The Kaiser–Meyer–Olkin (KMO) measure of sampling adequacy was .538, indicating only marginal adequacy for exploratory analysis. Therefore, the results of the subsequent principal component analysis should be interpreted with caution. Additionally, Bartlett's test of sphericity yielded statistically significant results ($p < .001$). The principal component analysis using an Oblimin rotation procedure revealed six factors with eigenvalues above 1, explaining a total of 63.619% of the variance. However, the variable "I have enough knowledge to use digital tools" was excluded, since it recorded an unsatisfactory result below .3 in the Communalities table. In the next step, the two variables "Digitalization increases my productivity" and "I rate my knowledge of digital technologies in agriculture as" were also excluded because they weighed more than one factor in the Pattern Matrix with a results above .3. Finally, the rotated solution yielded four interpretable factors or components with eigenvalues above 1, explaining a total of 58.294% of the variance (Table 10). The KMO score increased to .554. It is important to emphasize, however, that the factor structure reported in this study should be interpreted with considerable caution. The Kaiser–Meyer–Olkin (KMO) measure of .554 and the unsatisfactory Cronbach's alpha coefficient (.401) indicate that the DF-10 scale does not meet the conventional criteria for reliability and construct validity. Consequently, the factors identified through principal component analysis are not presented as validated thematic dimensions, but rather as exploratory patterns that may inform future hypothesis generation. Any substantive interpretation of these factors would require replication on a larger, more representative sample, using a revised and pilot-tested measurement instrument.

Table 10. Pattern Matrix[a]

	Component			
	1	2	3	4
Digitalization helps reduce the use of pesticides	.860			
Digitalization contributes to the competitiveness of my farm	.832			
I use digital methods for traceability	.711			
I am satisfied with the technical support provided by digital solution suppliers		.884		
Digital technologies reduce my costs		.860		
I use the internet daily for agriculture information			.664	
I believe that digital technologies contribute to sustainable agriculture			.613	
Subsidies would motivate me to adopt more digital tools			.511	
I plan to expand the use of digital technologies in the next two years				.765
Digitalization will improve market access				.714
Extraction Method: Principal Component Analysis. Rotation Method: Oblimin with Kaiser Normalization. a. Rotation converged in 6 iterations				

Source: Authors' calculations

The reliability analysis of the new 10-item DF scale showed improvement, with Cronbach's alpha increasing to .401. However, this indicates that the internal consistency of the new DF scale or DF-10 scale was still unacceptable. We checked the correlation between this new DF-10 scale and the Obstacles to DF scale. Although the coefficient was now negative, as expected, a non-significant, very weak, close to zero correlation was recorded between these two scales, $r = -.036, n = 170, p = .637$. The exploratory principal component analysis yielded four tentative components. However, given the low internal consistency of the scale and the marginal KMO value, these components should not be considered stable or validated dimensions. They are reported solely as descriptive outcomes of the exploratory analysis, and no substantive interpretation or policy implications are derived from their structure. Further research should first develop and validate a more reliable measurement instrument before examining the dimensional structure of digital literacy among farmers.

Regression analysis

To directly test the hypothesis that digital literacy is associated with readiness for digital transformation (H1), a multiple linear regression analysis was conducted using the enter method. The dependent variable was the item „Overall readiness of my farm for digital transformation" (Item 17). The independent variables included self-rated knowledge of digital technologies (Item 2), perceived sufficiency of knowledge to use digital tools (Item 4), daily use of the internet for agricultural information (Item 6), and intention to expand the use of digital technologies in the next two years (Item 9). The regression model was not statistically significant ($F(4, 165) = 1.662$, $p = .161$),with an R^2 of .039 and an adjusted R^2 of .015. This indicates that the selected predictors explain only a small and non-significant proportion of variance in farmers' readiness for digital transformation. None of the individual predictors reached statistical significance (p > .05 for all coefficients). These findings suggest that, within this

sample, the selected indicators of digital literacy do not significantly predict overall readiness for digital transformation. However, due to the previously noted limitations regarding scale reliability and the use of a single-item dependent variable, these results should be interpreted as preliminary and warrant further investigation. It is possible that other unmeasured factors—such as access to infrastructure, financial resources, social influence, or prior experience with digital technologies—play a more important role in shaping farmers' readiness for digitalization.

Comparison of the group means

A series of t-tests was conducted to examine the impact of additional reserve variable, listed as variable number 17 in Table 1, "Overall readiness of my farm for digital transformation", an dependent continuous variable, on the three socio-demographic independent variables. No statistically significant differences were observed based on sex $(t(168) = 0.455, p = .650)$, level of education $(t(168) = 0.340, p = .734)$, and place of residence $(t(168) = -1.312, p = .191)$.

Moreover, a series of t-tests was conducted to examine the impact of dependent continuous variable "Overall readiness of my farm for digital transformation", on the four closed-ended research questions' independent variables. No statistically significant differences were observed based on the "Do you track income and expenses digitally?" variable $(t(168) = 0.455, p = .650)$, on the "Do you use credit for business operations?" variable $(t(168) = 0.933, p = .352)$, on the "Frequency of using digital technologies" variable $(t(168) = -0.801, p = .424)$, and on the "Main obstacles to introducing digitalization" variable $(t(168) = 0.418, p = .677)$. For socio-demographic independent variables with more than two groups, a series of ANOVA tests were conducted. The dependent variable was the "Overall readiness of my farm for digital transformation" variable, as in the previous tests. There was not the significant difference observed among the three level of farm size groups $(F(2,167) = 0.085, p = .919)$, or the four level of production sector groups $(F(3,166) = 0.179, p = .910)$, However, a significant difference was observed among the three level of age groups $(F(2,167) = 9.061, p < .001, \eta^2 = .098)$. The effect size, determined through eta squared, was .098, which means that the actual difference in mean scores between the groups was medium. Post-hoc comparisons using the Tukey HSD test indicated that the mean score for age group 18-30 $(N = 16, M = 3.375, SD = 0.500)$ was significantly different from age group 31-55 $(N = 105, M = 3.019, SD = 0.416)$. Moreover, the mean score for age group 31-55 $(N = 105, M = 3.019, SD = 0.416)$ was significantly different from age group 56-70 $(N = 49, M = 3.286, SD = 0.456)$. The results indicate that the youngest age group reported the highest mean readiness for digital transformation, followed by the oldest age group, while the middle-aged group reported the lowest mean readiness. However, the present data do not provide sufficient evidence to explain the reasons underlying the observed differences between age groups. These differences may be associated with factors not examined in this study and therefore require further investigation. However,

given that this analysis relied on a single-item dependent variable, these findings should be treated as exploratory and interpreted with caution. Finally, a series of ANOVA test was conducted to examine the impact of dependent continuous variable "Overall readiness of my farm for digital transformation", on the three closed-ended research questions' independent variables with more than two groups. No statistically significant differences were observed based on the "Investments in modernization in the last 3 years (EUR)" variable $(F(3,166) = 0.179, p = .910)$, on the "I use the following technologies" variable $(F(3,166) = 0.416, p = .742)$, and on the "Most important priority for the next two years" variable $(F(2,167) = 0.311, p = .733)$.

Conclusion

This paper analyzes the level of digital literacy and readiness for digital transformation among farmers in the Republic of Serbia, with particular emphasis on the economic and information-technology dimensions of agricultural digitalization. The study contributes to the existing literature by providing empirical evidence from a transition economy in which the digital transformation of agriculture remains uneven and is strongly conditioned by human capital constraints. The findings indicate that basic digital tools—such as mobile applications and online sales channels—are relatively widely adopted, whereas the use of advanced digital technologies remains limited. Several methodological limitations of this study must be acknowledged. First, the final sample consisted of 170 farmers who voluntarily agreed to participate from an initial sampling frame of 422 farmers. Since participation was based on respondents' willingness to take part rather than random selection, the sample may be subject to self-selection bias. Farmers who agreed to participate may differ systematically from those who declined, particularly in their interest in or familiarity with digital technologies. Therefore, although the sample is adequate for exploratory purposes, the findings should not be generalized to the broader population of Serbian farmers without caution. Second, the digital literacy scale used in this study demonstrated low internal consistency (Cronbach's $\alpha = .401$), which undermines the reliability of any conclusions drawn from the factor analysis. Third, the dependent variable „Overall readiness for digital transformation" was measured using a single Likert-type item rather than a validated multi-item scale. Single-item measures, while occasionally used in exploratory research, do not possess the psychometric robustness of composite scales. Fourth, the factor structure identified through PCA should not be interpreted as validated thematic dimensions, but rather as exploratory patterns requiring further empirical scrutiny. Fifth, the regression model was not statistically significant, which indicates that the present data do not provide sufficient statistical evidence of a relationship between the selected indicators of digital literacy and readiness for digital transformation. Future research should focus on developing and validating a comprehensive digital literacy instrument specifically tailored to the agricultural context in Serbia, employing larger and more diverse samples, and incorporating qualitative methods to gain deeper insights into farmers' perceptions and needs. These findings point to potential disparities in digital technology adoption

and digital competencies among the surveyed farmers. The findings indicate that insufficient knowledge and digital skills represent an important barrier to the broader adoption of digital technologies. Based on the empirical findings, the research hypotheses were evaluated as follows. Hypothesis H1, which posits a statistically significant relationship between farmers' digital literacy and their readiness for digital transformation, was not supported. The multiple linear regression model was not statistically significant ($F(4, 165) = 1.662$, $p = .161$), and none of the individual predictors reached statistical significance. Therefore, the present findings do not provide sufficient statistical evidence of a significant relationship between the selected indicators of digital literacy and farmers' overall readiness for digital transformation. Hypothesis H2 proposed that more frequent use of digital technologies in agricultural production and business operations is associated with more positive perceptions of the benefits of digitalization. Although the descriptive findings indicate relatively frequent use of digital technologies and generally positive perceptions of several benefits of digitalization, this relationship was not directly tested using an appropriate inferential statistical procedure. Therefore, H2 cannot be statistically confirmed on the basis of the present analysis and should be regarded as not formally tested. Hypothesis H3 proposed that a lack of knowledge represents a more significant barrier to digitalization than legal and institutional constraints. The descriptive findings provide support for this hypothesis, as 77.05% of respondents identified lack of knowledge as the main barrier, compared with 22.94% who identified legal obstacles. However, because this comparison was based on descriptive frequencies rather than an inferential statistical test, H3 should be interpreted as descriptively supported rather than statistically confirmed. In addition, the cross-sectional and self-reported nature of the data may involve subjective response bias and does not allow for causal inference. Accordingly, future research should employ larger and more representative samples, longitudinal research designs, and advanced econometric methods to examine causal relationships between digital literacy, technology adoption, and economic performance indicators such as productivity, costs, and profitability. Furthermore, comparative studies across different regions or countries would enhance the robustness and international relevance of findings in the field of agricultural digital transformation.

Conflict of interests

The authors declare no conflict of interest.

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SERBIAN WINE SECTOR LEGAL REFORM: CLUSTER INSTITUTIONALIZATION AND PROTECTION OF GEOGRAPHICAL INDICATIONS

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ABSTRACT

The Serbian wine sector is facing a profound structural crisis, despite the existing legal frameworks and strategic documents. The article legally and economically analyzes Serbia's viticulture and wine sector aiming to identify a structural crisis and propose mitigation measures. Four hypotheses are tested using an interdisciplinary methodology encompassing: (1) analyzing 2019-2023 production indicators utilizing UN Food and Agriculture Organization data; (2) a normative analysis of Serbia's current Law on Wine; and (3) a French, Spanish, and Italian institutional model comparative analysis. The results demonstrate a continuous decline in key parameters despite the 2021-2031 Serbian Viticulture and Winemaking Development Program. Furthermore, the findings indicate that current legislation inherits a passive-control model, systematically ignoring producer economic organization. The article concludes that sector's survival requires an urgent legal and strategic revision, targeted at institutionalizing wine clusters and legal geographical indication definition in compliance with EU Regulation 2024/1143.

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Introduction

Wine has historically played a significant role within Serbia, serving not merely as a commercial market commodity, but as an integral cultural lifestyle element, particularly in rural households where climatic conditions permitted viticulture. This production, frequently oriented toward self-consumption, underscores primarily perceiving wine as a food product, an essential dietary component, and a family custom, rather than an alcoholic beverage. This conceptualization is reinforced by the current Serbian Law on Wine, which defines it as an "agricultural-food product" (Art.5, paragraph 4, Law on Wine, 2012), and is scientifically supported by numerous studies highlighting the health benefits associated with moderate consumption (Ilak Peršurić et al., 2023).

Serbian viticulture and winemaking constitute a major economic sector possessing substantial further development potential. Despite a continuous, long-standing legal tradition, including enacting the first Law on Wine in 1929, the viticultural and wine sectors face numerous challenges. These challenges encompass legal, economic, and social dimensions, thereby requiring a comprehensive, multidisciplinary approach given the complex nature of wine, spanning agricultural production to commercial trade. Addressing these intricate issues necessitates robust theoretical legal frameworks to guide sector reforms. Within recent literature, particularly concerning the Western Balkans, systematic viticultural legal aspect studies remain rare (Ducman et al., 2023).

Historical regulatory continuity demonstrates that the state has consistently treated wine as a strategic product, a revenue source, a stability factor, and a cultural identity element. Nevertheless, this continuity underscores an ongoing struggle between formal regulations and market reality. Within the medieval Serbian state, the regime's relationship of wine was primarily economically motivated. King Stefan Milutin's 1300 Charter established an early trade monopoly, granting the Monastery of Saint George exclusive wine retailing rights (Stojičić, 2002). This public law intervention was expanded via Dušan's Code, which protected vineyards as "noble property" while imposing strict sanctions for damaging them (Solovjev, 1980). Consequently, wine became permanently established as a legal asset possessing exceptional state importance under detailed state control (Blagojević, 1973).

This approach persisted throughout the 19th century. The 1844 Serbian Civil Code (SCC) distinguished wine and vineyards as specific, alienable, and inheritable property. Wine escaped standard household chattel classification, thereby enabling free circulation subject to a distinct contractual obligation requiring a "wine-tasting" condition (Art. 574 and 645, SCC). Subsequently, the 1882 phylloxera crisis accelerated regulatory framework formalization. The 1889 viticultural statistics recorded over 43,000 vineyard hectares, confirming this sector as a pivotal economic pillar within the then Kingdom of Serbia (State Statistics of Serbia, 1889). This systemic intervention demand yielded the 1921 Vineyard Restoration and Improvement Act (within the Kingdom of SHS) and the 1927 Special Wine Trading Usages (Art. 35), culminating in the 1929 Kingdom of Yugoslavia's first specialized Law on Wine. However, a profound rift between the

legislative framework and market reality emerged immediately through the so-called Yugoslav Wine Trade Crisis, characterized by lack of competitiveness and inefficient state agreements (Savić et al., 2022). This historical precedent demonstrates that legislation alone remains ineffective lacking flexible mechanisms enabling producers' collaborative market action.

Regional wine history reflects an ongoing legal dialogue conditioned by wine's dual nature as both a luxury commodity and an essential food product (Jovanović, Atanasovska Cvetković, 2022). This ambivalence compels state intervention to balance fiscal interests against commodity quality and origin protection (Jovanović, 2022). This historical constant – wine acting simultaneously as a fiscal object and a protected asset – solidified a reactive administrative control model rather than market development support. The aforementioned historical-legal sources remain relevant because they prove that this matrix (monopoly, surveillance, sanctions) persist today, explaining why current legislation continues emphasizing control over producer economic organization. However, while leading European wine-producing nations pivoted toward association and innovation models, Serbian regulations, via the 1973, 1994 and 2009 laws on wine, retained this anachronistic, fiscal-control approach.

Hence, this study originates from analyzing the viticultural and wine production structural crisis, alongside grape variety structural dynamics, to highlight imperative systemic solutions. By executing a critical current Law on Wine review and incorporating comparative European model insights, this research identifies key industry challenges and offers concrete, legally grounded solutions. The article's core thesis argues that the Serbian wine sector's structural crisis stems from a strategic desynchronization between the historically embedded fiscal-control regulatory model and modern market demands, therefore, the solution requires wine cluster institutionalization and legal geographical indication definition. The research significance is threefold: theoretical (strategic desynchronization concept), empirical (documenting declining 2019-2023 production indicators), and normative (providing concrete Law on Wine amendment proposals inspired by three successful models while harmonizing with EU Regulation 2024/1143).

This study's primary subject encompasses a legal-economic analysis targeting the Republic of Serbia's viticultural and wine sector, operationalized through the following objectives: (a) determining the existence and structural scope of the Serbian viticultural and wine sector crisis based on 2019-2023 production indicators; (b) conducting a critical Law on Wine normative analysis to identify systemic regulatory deficiencies; (c) evaluating French, Spanish, and Italian institutional models comparatively; and (d) formulating concrete Law on Wine amendment proposals to enable cluster institutionalization and geographical indication protection.

This study addresses the following primary research question: Why does the Serbian viticultural and wine sector, despite possessing a formal regulatory framework and strategy, experience a continuous decline in key production parameters, and which

institutional mechanisms could halt this crisis? Extant literature surrounding Serbia's viticultural and wine sector predominantly addresses agrotechnical and geographical aspects, thoroughly neglecting an interdisciplinary legal-economic regulatory framework analysis and institutional reform. Consequently, this paper fills this exact gap.

Based on the presented thesis, this study tests the following hypotheses:

H1: There is a justified assumption that the continuous decline in key production parameters within the Serbian wine sector (2019-2023) is linked to a structural mismatch between the historically rooted fiscal-control regulatory model and modern market demands, with this mismatch manifesting through the absence of institutional mechanisms to encourage producer economic organization

H2: The current Law on Wine contains a legal vacuum, the complete absence regarding producer economic organization provisions, rendering it incapable of stimulating cluster development.

H3: Introducing mandatory producer membership (inspired by French, Spanish and Italian models) for those using geographical indications creates institutional assumptions for improved internal quality control and market presence coordination, thereby, alongside other factors (such as marketing strategy, vintage quality consistency, production technology modernization), enhancing Serbia's overall market position.

H4: A value-based financing model (turnover percentage and certification fees) represents an economically more equitable framework compared to the existing vineyard area-based model, while its stimulative effect on producer behavior remains a premise requiring empirical verification through future research.

Following these hypotheses' verification through production indicator analysis, alongside normative and comparative reviews, the final section deduces conclusions and proposes concrete Law on Wine amendments.

Materials and Methods

Aligned with the hypotheses (H1-H4), this study implements an interdisciplinary approach enabling their verification through four interconnected steps: (1) an empirical structural crisis diagnosis; (2) a current Law on Wine normative analysis; (3) a comparative French, Spanish and Italian institutional model review; and (4) formulating *de lege ferenda* reform proposals.

Hypothesis H1 (arguing that strategic desynchronization causes the crisis) is tested by analyzing 2019-2023 production indicators based on official United Nations Food and Agriculture Organization (FAO) data and the 2023 Statistical Office of the Republic of Serbia Agriculture Census. Calculated absolute and percentage changes in harvested areas, yields, alongside grape and wine production (Table 1) enable trend determination and subsequent linkage to the regulatory character.

Hypothesis H2 (identifying a Law on Wine legal vacuum) is verified through a normative content analysis addressing the current Law on Wine provisions ("Official Gazette of Republic of Serbia" no. 41/2009 and 93/2012). The provisions are categorized into thematic unit (technical conditions, control, geographical indication and producer organization). Special attention targets determining the existence regarding producer economic organization provisions, whose absence constitutes a legal vacuum.

Hypotheses H3 and H4 (addressing institutional reform and the financing model) are tested utilizing the comparative method. A comparative analysis converting three leading EU wine-producing countries (France, Spain and Italy) was executed, based on primary legal sources, *Code rural et de la pêche maritime*, *Ley* 24/2003 and *Legge* 238/2016, alongside the new EU Regulation 2024/1143, whereby H3 does not claim that the analyzed institutional mechanisms are sole factors influencing quality and market position, but rather evaluates their significance within the overall regulatory framework, acknowledging other relevant factors (agrotechnical, climatic, economic, marketing). The H4 comparative analysis contrasts the area-based and value-based financing models. The proposed model appears more equitable (burden proportional to turnover), whereas its stimulative effect is excluded from empirical testing due to data limitations, remaining at a theoretical level. The benchmarking criteria encompass: the geographical indication protection legal basis, institutional bodies (*ODG, Consejos Reguladores, Consorzi di tutela*), mandatory membership, control mechanisms, financing models and sanction systems. This process identifies best practices capable of inspiring Serbian legislative amendments.

Synthesizing all hypotheses' verification results, the final section formulates concrete *de lege ferenda* Law on Wine amendment proposals (incorporating a new Article 6a, Producer Consortiums, Control Councils, mandatory membership, dual-source financing utilizing a 0.5-1% turnover percentage alongside certification fees and a designation right revocation mechanisms).

Research limitations include missing 2023 wine production data within the FAO database alongside a complete official data absence regarding all indicators 2024 and 2025.

Results and discussion

Empirical Analysis

The central research finding, empirically confirming deep-seated Serbian viticulture and winemaking structural issues, is summarized in Table 1. This table presents fundamental production indicator dynamics for 2019-2023, utilizing current official FAO Serbia data to render the structural degradation trend indisputable. The analytical framework also encompasses the initial three years of the Republic of Serbia Viticulture and wine Production Development Program (2021 – 2031) implementation ("Official Gazette of the Republic of Serbia" no. 154, December 23, 2020), thereby facilitating the initial impact assessment.

Table 1. Serbian Viticulture and Wine Production Structural Crisis (2019-2023)

Year	Harvested Area (ha)	Grape Yield (kg/ha)	Grape Production (t)	Wine Production (t)
2019	20 501.0	7 976.0	163 515.0	30 184.0
2020	19 840.0	8 080.0	160 307.0	27 273.0
2021	20 113.0	7 742.0	155 718.0	26 550.0
2022	19 973.0	8 135.0	162 481.0	25 982.0
2023	18 349.0	7 168.0	131 526.0	-
Variance (2019 – 2023)	↓ - 2 152 ha	↓ - 808 kg/ha	↓ - 31 990 t	↓ - 4 202 t (2019 – 2022)
Percentage Variance %	↓ - 10. 5%	↓ - 10.1%	↓ - 19. 6%	↓ - 13. 9% (2019 – 2022)

Source: Food and Agriculture Organization (FAO) https://www.fao.org/faostat/en/#data/QCL; Authors' analysis

Distinct from occasional bad-year weather oscillations, the five-year series (2019-2023) uncovers three deep-seated structural issues:

First, a continuous rather than temporary key indicator decline – affecting harvested areas, yields, and overall grape and wine production, removes individual poor seasons as a primary cause. The crisis manifests through a threefold continuous decline: harvested area contraction (-10.5%), production efficiency deterioration (yields decreasing by 10.1%), alongside a total grape (-19.6%) and wine (-13.9%) production collapse.

Second, the simultaneous resource volume, production efficiency and ultimate output decline evidences a general sector-wide degradation rather than isolated, standalone issues.

Third, these negative trends persisted even after the 2021-2031 Development Program adoption, with 2023 recording the most drastic contraction, reducing harvested area to 18 349 ha, yields to 7 168 kg/ha and grape production to 131 526 t. Despite identifying fundamental deficiencies (land fragmentation, low yields, together with a weak market position) and establishing noble goals, the Program fails to deliver operational legal and institutional execution mechanisms. Consequently, the existing strategic framework leaves the core crisis causes unaddressed, remaining a mere declaration. Accordingly, an incentive structure oriented toward *status quo* maintenance rather than strategic restructuring and innovation support emerges as the entire regulatory system's fundamental flaw. Ultimately, these empirical indicators represent the systemic structural crisis's quantifiable manifestation.

Table 1 results provide an empirical basis supporting hypothesis H1: the observed continuous decline in harvested area (-10.5%), yield (-10.1%), and grape (-19.6%), and wine production (-13.9%) during the 2019-2023 period, despite implementing the 2021-2031 Development Program points to a possible structural mismatch between the historically rooted fiscal-control regulatory model and modern market demands. Although this trend exceeds typical annual fluctuations, pointing to deeper structural

problems, a causal link with the regulatory model cannot be inferred solely from five-year data. Further research addressing other potential factors (climatic, economic, social) is necessary.

The 2023 Agriculture Census (Statistical Office of Republic of Serbia) provides additional confirmation: although Serbia possesses 3 239 734 ha utilized agricultural area (UAA), orchards and vineyards constitute a mere 6.62% within this territory. Non-Geographical Indication (non-GI) varieties dominate the structure (57%), whereas geographical indication (GI) varieties account for barely 16% (Table 2). This structural division further illuminates the sector's market position, reflected in an orientation toward non-GI production, standing in direct contrast with contemporary market demands.

Table 2. Grape Variety Structural Distribution (2023)

Variety Classification	Percentage
Non-Geographical Indication (non-GI) Varieties	57%
Geographical Indication (GI) Certified Varieties	16%
Table Grapes	24%
Other Purpose Grapes	3%
Total	100%

Source: 2023 Agricultural Census, Statistical Office of the Republic of Serbia, Belgrade 2024 https://popispoljoprivrede.stat.gov.rs/media/31092/brosura-srpski-sa-koricom.pdf

Table 2 illustrates the grape varieties structure. As demonstrated, nongeographical indication (non-GI) varieties heavily dominate, whereas the geographical indication (GI) varieties remain relatively low.

Current Wine Law normative analysis: structure, deficiencies and consequences

Diagnosis reveals a paradox: a detailed piece of legislation meticulously controlling individual producer technology inherently ignores comprehensive sector' economics. This legal vacuum, the absolute lack of provisions enabling or encouraging producer economic organization, is directly responsible for chronic fragmentation and an inability to establish a strong national brand. Therefore, the strategic reform essence lies not in adding further technical regulations, but rather in expanding and reorienting the regulatory framework itself.

The Serbian wine producers may register under various statutory forms provided by the Companies Act aiming at a for – profit purpose (Art. 2, Companies Act, "Official Gazette of the Republic of Serbia" no. 36/2011, 99/2011, 83/2014 – other law 5/2015, 44/2018, 95/2018, 91/2019, 109/2021 19/2025). The most common organizational forms include: sole proprietorship, limited liability company (LLC) or registered agricultural entity. According to Business Registers Agency (BRA) data, Serbia currently lists 491 registered entities (legal entities and entrepreneurs) with wine production as their primary business. This relatively small producer count could facilitate organized association (what leading European wine nations term a cluster),

however, this remains unachieved due to lacking legal incentives and institutional support frameworks.

In Serbian jurisprudence, wine is regulated through separate law, the Law on Wine ("Official Gazette of the Republic of Serbia", nos. 41/2009 and 93/2012). This law maintains *lex specialis* status relative to general regulations, meaning other statutory provisions apply only where the Law on Wine does not regulate otherwise. Crucially, the Law on Indications of Geographical Origin ("Official Gazette of the Republic of Serbia", nos. 18/2010 and 44/2018) explicitly excludes wine (Art. 1), leaving wine geographical origin protection (GOP) entirely within the Law on Wine's purview. This legal disparity yields far-reaching consequences – the Law on Wine framework fails to fully or adequately establish GOP system. Without a clear definition, neither adequate wine protection nor commercial GI exploitation as a market positioning tool remains possible. Namely, Article 33 prescribes specific GI wine categories, emphasizing mandatory designations: the primary geographical indication, the traditional expression (encompassing quality categories and additional designations), and the recognized traditional term. A particular problem stems from the law's structure, which focuses almost exclusively on production processes (Arts. 16-26). These provisions meticulously dictate wine production requirements, record-keeping methods, accompanying documentation content, product technical characteristics, and quality control procedures. Such an approach results in chronic sector fragmentation. Although Serbian Business Registers Agency (BRA) records indicate that wine-producing associations exist within every defined Serbian wine region (such as the Winemakers and Viticulturists Association Leskovac, the "Subotica Region" Geographical Indication Association, the "Srem – Fruška Gora" Grape and Wine Producers Geographical Indication Association and the Šumadija Winemakers Association), they function merely as interest groups, lacking regulatory and statutory powers to manage GI or enforce quality control. They remain untransformed into executive bodies exercising delegated public powers, contrasting sharply with leading wine-producing nations. Indicatively, the law completely omits provisions regarding: producer economic organization, producer association, joint market entry, collective GI management, unified domestic and international marketing or collective quality responsibility mechanisms. This legal vacuum breeds a systemic asymmetry: the state meticulously regulates wine production, yet fails to erect a legal framework enabling producers to organize economically and penetrate markets collectively. Lacking reliable empirical data, any further causal inquiry would remain strictly speculative.

Alternative approach potential is best illustrated by French, Spanish and Italian examples. In these nations, legal regulations extend beyond technical provisions, creating institutional mechanisms for producer collective action (including quality control, geographical origin protection, and joint market entry). This collective GI management concept is further reinforced by the newly effective EU Regulation 2024/1143, which consolidates previously fragmented wine, agricultural product, and spirit drinks regulations into a unified legal framework. This Regulation explicitly

emphasizes that collectively acting producers possess the necessary authority and responsibility to manage geographical indications (Art. 19, EU Regulation 2024/1143). Consequently, identified Serbian Law on Wine deficiencies gain significance, indicating an urgent legislative intervention necessity.

In this context, the identified Serbian Law on Wine deficiencies gain added gravity, dictating urgent legislative intervention. Hypothesis H2 also stands confirmed: the Law on Wine normative analysis demonstrates absolute absence of provisions producer governing economic organization. This provision gap directly impedes wine cluster development.

Comparative overview: French, Spanish and Italian models

Wine clusters, defined as "geographic concentrations of interconnected companies and institutions within a particular field" (Porter, 1998), represent established practice across leading wine regions, from France, Spain and Italy to California and Chile. Within this context, their significance is emphasized through development potential, identifying innovation and technological learning as central functional concepts within wine producer clusters amidst rapid global wine industry transformation (Bell, Giuliani, 2007).

France provides a model in which the wine cluster concept builds upon the geographical origin protection system and the *Appellation d'Origine Contrôlée* (AOC) framework, regulated by the *Code rural et de la pêche maritime*. Protection and Management Organizations (ODGs) play a pivotal role as a producers' associations with delegated public authority: they draft specifications, participate in control plans and protect both names and territories (Art. L642-17, Code rural). Producers organize into defense syndicates (*Syndicats de défense*) to manage indications, while the National Institute of Origin and Quality (INAO) oversees control through locally delegated commissions (Art. L642-5 – L642-16, Code rural). This AOC system functions not merely as a legal protection framework but as the institutional core for cluster organization. While ODGs ensure collective quality and origin management, the cluster encompasses a broader research, educational and commercial network, collectively enhancing regional competitive potential (Baibakova et al. 2013, 10–16). Defense syndicate producers collaborate with research centers, creating the synergy underpinning French winemaking competitiveness (Fontagné et al. 2010, 3 – 24).

"The wine sector holds a prominent position within the Spanish agrifood industry, for both the quality and the variety of its production" (Marco-Lajara et al. 2022, 1). This standing is facilitated by the Ley 24/2003 de la Viña y del Vino statutory framework establishing the geographical origin protection system. Spanish legislation delegates significant competencies to Autonomous Communities, while the Ministry of Agriculture (MAPA) ensures national coordination. Managing designations of origin, *Denominación de Origen* (DO) for quality wines and *Denominación de Origen Calificada* (DOCa) for elite regions maintaining consistent high quality for at least ten years, is entrusted to Regulatory Councils (*Consejos Reguladores*). These councils

maintain registries, draft specifications, enforce compliance, promote indications and collaborate with research institutions (Art. 25–27, Ley 24/2003). *Consejos* membership for all protected indication producers ensures uniform quality standards. Research confirms the positive *Consejos* activity impact on export performance (Depetris-Chauvin, Fernández-Olmos, 2024), as Spanish wine clusters grow through collective brand reputation (Marco-Lajara et al. 2022). Synergy remains evident: while *Consejos* provide collective quality and origin management, clusters encompass a broader research and commercial network forging regional competitive potential.

Italy applies a similar institutional model, where the wine sector pioneered geographical origin protection development, establishing the regulatory foundation subsequently expanded to all food products (Gori, Alampi Sottini, 2014). This legal regime is codified through *Legge* 238/2016 (*Testo Unico del Vino*), ensuring designation management, *Denominazione di Origine Controllata* (DOC) and *Denominazione di Origine Controllata e Garantita* (DOCG), the latter requiring a mandatory state seal per Art. 48, *Legge* 238/2016, for Protection Consortia (*Consorzi di tutela*). Such legislation transformed consortia into interbranch organizations with expanded competencies encompassing specification drafting, inventory management, brand protection and supply-demand alignment projects (Gori, Alampi Sottini, 2014). A defining Italian model feature, established by Art. 64 (*Legge* 238/2016), is the strict management separation from technical verification. Independent control bodies (*Organismi di controllo*) conduct verification, eliminating conflict of interest and enabling consortia to act as strategic collective brand managers protecting product territorial integrity. Economic indicators confirm this model's positive impact: protected origin wines dominate Italian retail chains, as the protection system allows producers to transcend marketing strategy differences and achieve superior market performance (Dominici et al., 2024). *Consortia* – independent controller synergy ensures an unbreakable product – technology – territory link, rendering the Italian wine sector a global competitiveness leader (Casini et al., 2020).

These systems evolved over decades, building upon high social capital and trust levels. Their absence in Serbia represents a severe development obstacle, surmountable only by establishing clear success principles: a strict management – control separation, financial viability, precise and adequate regulation and wine cluster institutionalization.

A French, Spanish and Italian model comparative analysis supports Hypothesis H3. Establishing mandatory membership within producer consortia (Italy), regulatory councils (Spain) or defense syndicates (France), alongside independent control body existence, is among the pivotal institutional factors in successful geographical indication management. Consequently, deploying similar institutions, a Producer Consortium and Viticultural Control Councils, could significantly elevate Serbian wine quality and market positioning. Therefore, the proposed institutional mechanisms are recommended as a necessary, yet insufficient condition for sector advancement, given the influence of other factors (agrotechnical, climatic, economic, marketing) that likewise determine these parameters.

Strategic Reform Proposal: Cluster Institutionalization and Geographical origin indications

A French, Spanish and Italian prominent geographical origin and institutionalization model comparative analysis indicate shared successful GI management elements: a clear legal definition, institutionalized producer bodies wielding concrete competencies and independent quality control. Legitimacy within such models stems precisely from intertwined internal membership support and external state institution recognition (Cusin, Loubaresse, 2020). Harmonizing Serbian legislation with European standards is vital, as Serbian wine geographical origin designation remains dogmatically undefined and limited to passive administrative control. These comparative insights dictate specific Law on Wine regulatory reform proposals.

The current Serbian Law on Wine reveals a highly centralized, administrative-fiscal control model rather than a proactive developmental framework. Under the positive legal framework, Articles 27-29 and Articles 38-43, the state maintains an absolute monopoly over quality testing, sensory evaluation and geographical origin verification. The domestic framework nominally regulates geographical origin designations through production elaborates (Art. 39), mandatory state verification and regional inspectorates within the Ministry of Agriculture. This mechanism functions as a reactive technical administration, thereby constituting a strict supervisory model wherein control is executed by agricultural inspectors operating under the Ministry. Consequently, this mechanism systematically ignores wine sector economic organization, leaving producers fragmented and structural incapable regarding global market collaborative positioning.

Overcoming this legislative impasse and aligning domestic law under the prevailing EU Regulation 2024/1143 demands a comprehensive legal-strategic reform. The reform would not represent mere duplication of existing administrative restrictions, instead, it introduces a paradigm shift across four pivotal intervention categories. Despite Article 6 precisely defining viticultural areas, provisions enabling producers to organize and collectively manage GI remain absent. Introducing new article, Article 6a, is proposed, defining geographical origin as a distinct, territory-bound legal asset whose specific qualities, reputation, or other essential characteristics are fundamentally conditioned through its natural and human factors. The current legislative approach treats geographical origin primarily an administrative category designated for labeling and oversight under Chapter V. Ergo, this unequivocal, concrete definition transcends the Article 34 technical boundaries, elevating geographical origin protection toward collective intellectual property rights actively managed through the producers themselves, fully complying with Article 19 EU Regulation 2024/1143, which explicitly emphasizes that collectively acting producers must wield the necessary powers and responsibilities to manage geographical indications.

Under the current system, domestic wine associations exist merely as voluntary interest groups holding passive technical roles regarding the elaborate drafting (Art.39). Contrarily, this reform proposes a statutory framework enabling grape and wine

producers within a "protected designation origin geographical area" to establish a Wine Geographical Origin Producers Consortium. Inspired form the Italian *Consorzi di tutela* (Art, 41, Legge 238/2016) and the Spanish *Consejos Reguladores* (Arts. 25-27, Ley 24/2003), this consortium will gain provision recognition as an authorized wine industry-wide designation management body. While prevailing legislation delegates labeling regulation enforcement toward state-appointed external bodies, the proposed Consortium wields direct competencies in technical dossier creation and modification, inventory management, regional brand protection and proactive supply-demand balancing projects. To eradicate the fragmentation paralyzing the Serbian wine market, mandating consortium membership for every winery operating within defined "protected designation origin delimited zones" is necessary, thereby abolishing the previous voluntary membership framework. This shift would establish a unified regional standard, transforming individual competition into collective competitive potential.

The pivotal structural divergence from the current framework lies within the management and control institutional separation. Currently, pursuant to Articles 28, 29 and 38, state-authorized laboratories and directly minister-appointed commissions organize sensory evaluation and quality verification, while the state budget provides direct financial funding (Art.43). This model generates an administrative bottleneck and restricts flexibility.

The proposed reform introduces Viticultural Control Councils acting as autonomous, expertly-guided public enterprises. Relying upon the Italian concept (*Organismi di controllo*, experience pursuant to Legge 238/2016, Article 41, paragraph 5), these Councils must remain strictly separated from the Consortium market promotional activities. Transferring verification authority from state agricultural inspectors toward independent, specialized expert councils relives the state apparatus regarding administrative burdens. Every technical or qualitative violation would trigger immediate, internal council-driven geographical origin designation usage right revocation. Consequently, this mechanism successfully circumvents slow administrative inspection procedures and drastically increases regulatory enforcement efficiency. In this manner, a pivotal shift will be introduced into Serbian positive law. This institutional transition stands in stark contrast to the existing system, which mandates state-driven designation revocation through protracted, retroactive inspection or judicial proceedings after brand damage occurs. In contrast, decades-long successful European practice introduces autonomous, internal, and immediate regional stamp right suspension, thereby safeguarding collective brand reputation before the non-compliant product ever reaches the market.

Current Serbian regional association practice relies upon membership fees paid proportionally regarding each member total vineyard area share. Although this model ensures elaboration drafting stability, it remains economically rigid because it burdens producers based upon static hectares rather than actual market turnover within a given year. Instead regarding this capacity model, the proposed *de lege ferenda* arrangement introduces two aligned funding sources transforming the traditional system into a dynamic, market-value-based model: (a) the first source entails a Consortium members

fee amounting to 0.5% - 1% regarding generated turnover. To prevent revenue concealment, this obligation directly links toward the issued state record stamp volume (Art.31, Para. 3, Law on Wine), whereby the Consortium calculates the amount exclusively based upon the officially approved geographical origin wine quantity and its declared value.; (b) the second source comprises a Control Council certification fee funding physicochemical and sensory analyses per wine batch. This dedicated fee legally relies upon the existing Rulebook on Wine Evaluators List and Evaluator Remuneration Amount (Art. 5 sample-volume-based tariff classes), while institutionally integrating expert bodies from the Rulebook on Wine Sensory Evaluation Procedure and Methods, specifically the Sensory Evaluation Commission and its licensed members, into the decentralized regional cluster Control Councils.

Both fees collection remains conditioned upon the Law on Wine Article 31 record stamp issuance: wineries pay proportionally regarding the stamp-requested batch volume, thereby eliminating the free-rider problem, abolishing the reform utopia and transforming stamps from a mere fiscal tool, serving passive packaging enumeration, into the wine cluster economic self-sustainability primary driving instrument.

Within this decentralized system, the Ministry of Agriculture retains a supervisory role. Pursuant to the Law on Wine, Article 29, paragraph 4, it updates the Evaluators List and reviews the Control Council operational tariff legal compliance, eliminating any prior administrative approval necessity. This mechanism effectively safeguards small family wineries against potential monopolistic deviations.

Table 3. Systematic analysis regarding the current Law on Wine and the *de lege ferenda* proposal for wine geographical indication management

Reform Aspect	Current Serbian Framework	Proposed Reform (*de Lege Ferenda*)
Geographical Origin Legal Definition	Dogmatically undefined.	New Article 6a: Substantive legal definition treating geographical origin as a territory-linked collective intellectual property right.
Producers Institutional Organization	Voluntary associations holding a passive technical role. (Example: Pursuant to its Statute, Association of Winemakers and Winegrowers of Serbia remains a non-governmental, non-profit organization established indefinitely to achieve shared viticultural and vinicultural goals and interests unattainable individually.)	Mandatory Producer Consortium (Based upon the Italian Consorzi di tutela and Spanish Consejos Reguladores frameworks).

Quality Control and Verification	State-driven (Ministry, inspectors, and laboratories).	Viticultural Control Councils – autonomous expert bodies (based upon the Italian *Organismi di controllo* experience); enacting immediate, internal designation revocation.
Funding	Membership fees proportional regarding each member total registered district vineyard area share.	(1) Consortium Membership Fee: 0.5% through 1% regarding generated turnover, directly linked toward state stamps (Art. 31) and digital turnover record inspection. (2) Control Council Certification Fee: calculated utilizing electronic delivery notes.
Ministry Role	Direct command and control enforcement;	Supervisory Function: updating the evaluators list and reviewing operational tariff legal compliance.

Source: Autors' proposals

Hypothesis H4 remains accepted: the value-based funding model (0.5% - 1% regarding generated turnover and certification fees) demonstrates greater economic equity and incentive capacity compared to the current vineyard-area-based model (per hectare). Linking payments toward state record stamp issuance (Law on Wine, Article 31) additionally prevents revenue concealment and eliminates the free-rider problem. Italian experiences confirm that this funding method ensures collective body stability and independence.

Conclusion

Based on the historical context expounded in the introduction, a centuries-old state-driven wine fiscal control model, the conducted empirical, normative and comparative analysis enabled testing the four established hypotheses. As detailed within the "Result and Discussion" chapter, all four hypotheses remain accepted and confirmed, while not neglecting the influence of other potential factors (agrotechnical, climatic, economic, marketing) and the need for further research into comprehensive sector improvement, which leads to recommending supplementary measures from other fields. H1 is not rejected: empirical, normative, and comparative findings support the premise of a structural mismatch between the fiscal-control regulatory model and modern market demands. H2 remains confirmed: the current Law on Wine lacks producer economic organization provisions, permanently obstructing winegrower cluster development. H3 remains accepted: French, Spanish and Italian comparative models indicate the mandatory producer consortium membership and independent control councils represent significant institutional mechanisms capable of enhancing Serbian wine quality and market positioning. H4 is accepted: in terms of economic equity, the proposed financing model (turnover percentage alongside the certification fees) demonstrates advantages

over the existing model by distributing the financial burden more equitably, provided that further research is needed to determine whether and to what extent the proposed model stimulates producer behavior.

Proceeding the aforementioned findings, specific *de lege ferenda* amendments to the Law on Wine are proposed: defining geographical origin (new Article 6a), institutionalizing clusters through mandatory producer consortium membership, establishing an independent Viticultural Control Council, introducing the value-based funding model and enacting the immediate geographical origin designation usage right revocation model.

Implementing the proposed integrated model, Serbian legislation abandons an anachronistic, passive administrative oversight concept and enters a proactive, market-oriented wine sector management phase. This institutional decentralization not only fulfills strict European Union *acquis Communautaire* alignment demands but, through the Producer Consortium and Viticultural Control Council synergy, transforms geographical origin from a bureaucratic category into a powerful economic development mechanism. Simultaneously, the reform paves the way toward full integration into the European geographical origin protection system, aligning domestic legislation with EU Regulation 2024/1143, and establishes foundations regarding self-sustaining wine cluster development, a network comprising producers, research, and educational institutions, thereby reducing costs, fostering knowledge exchange, and facilitating joint domestic and foreign market appearance. This mechanism overcomes structural fragmentation, empowering Serbian winemaking to build a recognizable collective brand and secure equitable market positioning on the global wine map. Wine, as a living history and identity embodiment, deserves strategic state care through a model encouraging, rather than obstructing, its full potential realization as the Serbian cultural and economic identity pillar.

Conflict of interests

The authors declare no conflict of interests.

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ARTIFICIAL INTELLIGENCE AND SMART FARMING TECHNOLOGIES: DRIVING ECONOMIC EFFICIENCY AND SUSTAINABLE DEVELOPMENT IN MODERN AGRICULTURE

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ABSTRACT

The integration of artificial intelligence (AI) and smart farming technologies is transforming agriculture through data-driven decision-making and improved resource management. This study examines the economic and sustainability effects of AI adoption, focusing on production efficiency, costs, and environmental performance. A comparative analysis of farms using AI-based solutions and conventional farms was conducted. Results show that AI-supported farms achieve higher crop yields, greater input efficiency, and lower production costs. AI also promotes sustainable farming by optimizing water and fertilizer use and reducing environmental impacts. The findings demonstrate the economic potential of digital transformation and highlight the importance of policy support, digital infrastructure, and farmer education. The study provides quantitative evidence of AI-driven economic efficiency in Serbian transitional agriculture, offering insights for policy development and sustainable digital farming.

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Introduction

Modern agriculture faces a dual challenge: increasing productivity to meet rising global food demand while reducing environmental impacts and managing rising input costs (Balai et al., 2025; Jararweh, 2023). Artificial intelligence (AI) and smart farming technologies—including sensor networks, automated monitoring systems, and machine learning algorithms—offer potential pathways to address this challenge by enabling data-driven, precision-oriented farm management (Abdel-Basset et al., 2024; Hermanus, 2022).

However, empirical evidence on the economic and sustainability effects of AI adoption remains limited, particularly in transitional agricultural economies such as those in Southeast Europe (Aijaz et al., 2025; Ignjatović et al., 2025). Most existing research originates from developed agricultural systems (Western Europe, North America, China) and focuses either on technological performance or isolated economic outcomes, with few studies examining integrated efficiency-sustainability effects using rigorous comparative methods.

This study addresses these gaps by analyzing the impact of AI-based smart farming technologies on economic efficiency and sustainable resource use in agricultural production systems. The research focuses on the Republic of Serbia as a representative case of transitional agriculture characterized by gradual digital transformation, small-to-medium farm structures, and developing digital infrastructure.

Research objectives and questions

The main objective of this study is to quantify the effects of AI adoption on farm-level economic and sustainability performance. Specifically, the study investigates four research questions:

1. Does AI adoption improve economic efficiency (yield, costs, income, labor productivity) in agricultural enterprises?
2. Do smart farming technologies contribute to more sustainable use of water, fertilizers, and energy?
3. What relationship exists between digital technology adoption and farm productivity when controlling for farm size?
4. How do AI-supported decision systems influence farm management practices?

Paper structure

The remainder of this paper is organized as follows. Chapter 2 reviews the relevant literature on AI in smart farming, economic efficiency of digital agriculture, sustainability outcomes, and identifies research gaps. Chapter 3 describes the methodological framework, including sample design, data collection, variables, and analytical procedures. Chapter 4 presents empirical results. Chapter 5 discusses findings in relation to existing literature, acknowledges limitations, and suggests future

research directions. Chapter 6 concludes with theoretical, practical, and managerial implications, followed by policy recommendations.

Literature review

Artificial Intelligence in Smart Farming Systems

The integration of artificial intelligence (AI) into agricultural production systems represents a paradigmatic shift from traditional, experience-based farming to data-driven, precision-oriented management. Smart farming technologies encompass a broad spectrum of digital tools, including Internet of Things (IoT) sensor networks, satellite and drone-based remote sensing, automated machinery, and machine learning algorithms that collectively enable continuous monitoring, analysis, and optimization of agricultural processes (Abdel-Basset et al., 2024; Akkem et al., 2023; Denić et al., 2018). These technologies transform raw environmental and operational data into actionable intelligence, supporting farmers in making more informed decisions regarding irrigation scheduling, fertilizer application, pest detection, and harvest timing (Karunathilake et al., 2023).

The evolution toward "Agriculture 4.0" and emerging "Agriculture 5.0" frameworks positions AI as a central enabling technology. Unlike earlier precision agriculture approaches that relied primarily on GPS and basic sensors, contemporary AI systems employ deep learning, computer vision, and predictive analytics to process complex, multi-dimensional datasets (Holzinger et al., 2024). For instance, convolutional neural networks have been successfully deployed for disease detection from leaf images, while recurrent neural networks forecast crop yields based on historical weather patterns and soil conditions (Shaikh, Rasool & Lone, 2022). Furthermore, AI-powered decision support systems integrate real-time data streams from multiple sources, providing farmers with scenario analyses and optimized resource allocation plans (Jararweh et al., 2023).

Despite rapid technological advancement, the adoption of AI in agriculture remains uneven across regions and farm sizes. Developed agricultural economies—notably the United States, Netherlands, Germany, and China—have witnessed accelerated AI integration, supported by robust digital infrastructure, public research funding, and agtech startup ecosystems (Kanojia et al., 2024). In contrast, transitional and developing agricultural systems face persistent barriers, including limited broadband connectivity, high initial investment costs, fragmentation of land holdings, and gaps in digital literacy among farming populations (AlZubi & Galyna, 2023). These disparities underscore the importance of context-specific research examining AI adoption dynamics beyond technologically advanced settings.

Economic Efficiency of Digital Agriculture

Economic efficiency in agriculture is conventionally defined as the optimal utilization of productive inputs—land, labor, capital, water, and energy—to maximize output and profitability per unit of input (Mohamed et al., 2021). Digital agriculture technologies,

particularly AI-based systems, are hypothesized to enhance economic efficiency through multiple mechanisms. First, predictive analytics reduce production uncertainty by improving forecast accuracy for weather events, pest outbreaks, and market prices, thereby enabling proactive rather than reactive management (Singh et al., 2022). Second, automation and robotics substitute for increasingly scarce and expensive agricultural labor, reducing wage expenditures while maintaining or increasing operational precision (Vinod Chandra, Hareendran & Albaaji, 2024). Third, real-time monitoring and variable-rate application technologies minimize input waste, directly reducing costs for water, fertilizers, and pesticides (Kumari et al., 2025).

Empirical evidence from developed agricultural contexts supports these theoretical mechanisms. Walter et al. (2017) demonstrated that smart farming technologies in Swiss crop production systems reduced input costs by approximately 15-20% while maintaining yield levels. Similarly, Idoje et al. (2021) reported that AI-driven irrigation systems in water-scarce regions of Spain achieved water savings exceeding 30% without compromising crop quality. In the North American context, Sharma et al. (2023) documented that farms adopting integrated AI decision support systems experienced net income increases of 22-35% compared to conventional neighbors, primarily driven by optimized fertilizer application and reduced energy consumption for field operations.

However, the economic calculus of AI adoption is not uniformly positive across all contexts. Initial capital expenditures for sensor networks, software licenses, and farmer training can be substantial, creating adoption barriers for small and medium-sized enterprises (Aijaz et al., 2025). Moreover, the return on investment period varies significantly depending on crop type, farm size, and existing technological maturity. Gryshova et al. (2024) caution that premature or poorly implemented AI solutions may generate negative returns if data quality is inadequate or if farmers lack the technical capacity to interpret and act upon algorithmic recommendations. These conditional factors highlight the need for rigorous, context-specific economic assessments—particularly in transitional agricultural systems where empirical evidence remains scarce.

Sustainability Outcomes of AI Adoption

Sustainable agricultural development requires balancing productivity growth with environmental stewardship, resource conservation, and climate resilience (Balai et al., 2025). AI technologies are increasingly positioned as tools for achieving this balance through what has been termed "sustainable intensification"—increasing output from existing agricultural land while reducing environmental pressures. The potential sustainability benefits of AI in agriculture span multiple dimensions, including water conservation, nutrient management, energy efficiency, biodiversity protection, and greenhouse gas emission reduction (Raj & Prahadeeswaran, 2025).

Regarding water resources, AI-based irrigation scheduling systems integrate soil moisture sensors, weather forecasts, and crop evapotranspiration models to deliver precise water quantities only when and where needed. Kumari et al. (2025) documented

that such systems reduced irrigation water consumption by 25-40% across multiple crop types without yield penalties, with particularly pronounced effects in arid and semi-arid regions. Similarly, AI-optimized fertilizer application—often implemented through variable-rate technology guided by soil nutrient mapping and crop growth models—reduces nitrogen runoff and associated eutrophication of water bodies. Kanojia et al. (2024) reported that AI-guided nitrogen management achieved fertilizer reductions of 15-30% while maintaining or improving crop protein content.

Energy efficiency represents another sustainability pathway for AI in agriculture. Automated machinery guidance systems reduce redundant field passes, directly lowering diesel fuel consumption and associated carbon emissions (Holzinger et al., 2024). Furthermore, predictive analytics for harvest timing and post-harvest storage conditions minimize energy-intensive drying and refrigeration requirements. However, it is important to acknowledge potential rebound effects: the energy and material costs associated with manufacturing, operating, and disposing of AI hardware (sensors, servers, communication equipment) must be accounted for in full lifecycle assessments (Jararweh et al., 2023). Most existing studies focus narrowly on operational efficiencies, leaving questions about net environmental benefits unresolved.

Research Gap and Contribution of This Study

Synthesizing the literature reviewed above reveals several significant research gaps that the present study aims to address. First, most of the empirical research on AI adoption in agriculture originates from developed agricultural systems—particularly Western Europe, North America, China, and Australia. While these studies provide valuable theoretical and methodological foundations, their findings may not directly transfer to transitional agricultural economies characterized by different farm structures, institutional environments, infrastructure endowments, and digital readiness levels (Ignjatović et al., 2025). The Western Balkan region, including the Republic of Serbia, remains severely understudied despite undergoing rapid digital transformation in agriculture.

Second, existing research tends to examine economic and sustainability outcomes in isolation rather than as integrated dimensions of farm performance. Studies focusing on productivity gains often neglect environmental indicators, while sustainability-focused research frequently lacks rigorous economic accounting. This fragmentation obscures potential trade-offs or synergies between efficiency and environmental objectives, limiting the utility of research findings for policy design and farm-level decision-making (Kumari et al., 2025).

Third, methodological limitations characterize much of the existing literature. Cross-sectional designs with small sample sizes predominate, while econometric approaches that control for confounding farm characteristics—such as management quality, investment capacity, and farmer experience—remain uncommon. Few studies employ rigorous statistical comparisons between adopter and non-adopter groups with appropriate matching or control variables (Aijaz et al., 2025). Consequently, observed performance differences may be partially attributable to selection bias rather than AI adoption per se.

Fourth, no published study to date has quantitatively assessed AI adoption effects on farm-level economic efficiency in the Republic of Serbia or the broader Western Balkan region using econometric methods. This geographical and methodological gap is significant because transitional agricultural systems present unique characteristics: small average farm sizes, fragmented land ownership patterns, incomplete digital infrastructure, and agricultural extension systems still adapting to digital advisory roles.

The present study directly addresses these gaps through the following contributions:

1. *Geographic contribution*: This study provides the first empirical assessment of AI-driven economic efficiency in Serbian transitional agriculture, generating evidence from a previously understudied regional context.
2. *Integrated analytical framework*: By simultaneously examining economic indicators (yield, costs, income, labor productivity) and sustainability indicators (water, fertilizer, and energy consumption), the study captures potential efficiency-environment synergies within a single analytical design.
3. *Rigorous methodological approach:* The study employs a comparative design with statistical controls (t-tests, Pearson correlation, multiple linear regression) applied to a systematically sampled dataset of 82 farms, enabling more robust attribution of performance differences to AI adoption.
4. *Policy-relevant insights:* By quantifying adoption effects in a transitional context, the findings provide actionable evidence for policymakers designing digital agriculture strategies, subsidy programs, and extension services tailored to the region's specific conditions.

In summary, this literature review establishes that while the potential of AI and smart farming technologies for improving economic efficiency and sustainability is well-recognized conceptually, rigorous empirical validation from transitional agricultural contexts remains insufficient. The present study responds to this gap by delivering context-specific, methodologically robust evidence that advances both academic understanding and practical agricultural policy.

Methodology

Research Design

This study applies a quantitative empirical research design aimed at evaluating the economic and sustainability effects of AI and smart farming technologies in agricultural production systems. The research combines descriptive statistical analysis and econometric modelling to examine relationships between technology adoption, economic efficiency, and resource utilization.

The study follows a comparative approach by analyzing agricultural enterprises that have implemented AI-based smart farming technologies and those operating under conventional management practices. This design enables the assessment of differences

in productivity, cost structure, and sustainability indicators between technologically advanced and traditional farms.

Study Area and Sample Selection

The empirical research was conducted on agricultural enterprises located in Republic of Serbia, representing transitional agricultural economies characterized by gradual digital transformation and increasing adoption of precision farming technologies. Data were collected from 82 agricultural farms operating in crop production and mixed farming systems during the production seasons 2023–2025.

The sample was drawn from the Serbian Agricultural Business Registry using stratified purposive sampling. Farms were stratified by size class (small: <20 ha; medium: 20–100 ha; large: >100 ha) and production type (crop vs. mixed). Within each stratum, farms were randomly selected to ensure representativeness. The sampling frame included 1,247 registered commercial farms in the region, with the final sample size (n=82) determined to achieve a 95% confidence level and 10% margin of error.

The farms were divided into two groups:

- Group A (AI-adopting farms): 41 farms using smart farming technologies, defined as farms that have implemented at least one of the following AI-based systems during the 2023–2025 production seasons: (a) sensor-based real-time monitoring systems (soil moisture, temperature, nutrient levels); (b) AI-driven decision-support software for irrigation, fertilization, or pest management; (c) automated variable-rate application technologies; or (d) predictive analytics tools for yield forecasting and harvest optimization. Farms in this group had been using these technologies continuously for at least one full production cycle prior to data collection.
- Group B (conventional farms): 41 farms applying traditional management methods without AI-supported systems.

The selected farms vary in size from 15 to 250 hectares (average 85 hectares), ensuring representativeness across small, medium, and large agricultural enterprises.

Data Collection

Data were collected using a combination of:

- structured farm management surveys,
- production and financial records,
- sensor-generated operational data,
- interviews with farm managers,
- digital platform reports from smart farming systems.

The collected dataset includes economic, production, and environmental indicators measured annually. All data were anonymized and standardized before statistical analysis.

Variables and Indicators

To evaluate the economic and sustainability impact of AI adoption, the study defines dependent and independent variables.

Independent Variable

Level of digital technology adoption (binary variable: AI adoption = 1; non-adoption = 0).

Dependent Variables

Economic indicators:

- Crop yield (tons/hectare)
- Production cost (EUR/hectare)
- Net farm income (EUR/hectare)
- Labour productivity (output per worker)

Sustainability indicators:

- Water consumption (m^3/hectare)
- Fertilizer usage (kg/hectare)
- Energy consumption (kWh/hectare)

Control Variables

- Farm size (hectares)
- Type of production
- Farmer experience (years)

Construction of the Economic Efficiency Index (EEI)

The Economic Efficiency Index was constructed as a composite measure using the following formula:

$$EEI = \frac{Z_{Yield} + Z_{Income} + Z_{Labour} - Z_{Cost}}{4}$$

Where:

EEI = composite Economic Efficiency Index;

Z_{Yield}= standardized crop yield of farm *i* (t/ha);

Z_{Income}= standardized net farm income of farm *i* (€/ha);

Z_{Labour}= standardized labour productivity of farm *i* (output per worker);

Z_{Cost}= standardized production cost of farm *i* (€/ha).

All variables were transformed using min-max normalization to ensure dimensional comparability across heterogeneous economic indicators:

$$Z_i = \frac{X_i - X_{min}}{X_{max} - X_{min}}$$

Where:

Z_i= observed value for farm *i*;

X_{min}= minimum observed value within the sample;

X_{max}= maximum observed value within the sample.

The composite index integrates four core dimensions of farm-level economic performance: productivity, profitability, labour efficiency, and cost rationalization. Variables positively associated with economic performance (yield, net income, and labour productivity) enter the index with positive signs, whereas production costs enter with a negative sign due to their inverse relationship with economic efficiency.

Higher EEI values indicate superior economic performance characterized by higher output productivity, greater profitability, more efficient labour utilization, and lower relative production costs. The index therefore provides a synthetic quantitative measure suitable for comparative statistical and econometric analysis of farm-level efficiency under different technological adoption regimes.

The index was standardized to a 0-1 scale using min-max normalization. A higher EEI indicates superior economic efficiency, defined as maximizing output and income while minimizing input costs.

Equal weighting was applied to avoid disproportionate influence of individual indicators and to preserve methodological neutrality in the aggregation process. This approach is consistent with established practices in composite index construction for agricultural performance assessment (OECD, 2008; Latruffe et al., 2017), where normative weighting is preferred in the absence of empirically derived preference parameters.

Statistical Analysis

Statistical analysis was conducted using R statistical software (version 4.3) and Microsoft Excel for graphical visualization.

The following analytical methods were applied:

1. Descriptive statistics

– Mean values

– Standard deviation

– Minimum and maximum values

2. Comparative analysis

– Independent samples *t-test* to evaluate differences between AI-adopting and conventional farms.

3. Correlation analysis

– Pearson correlation coefficient to examine relationships between AI adoption and economic indicators.

4. Regression analysis

– A multiple linear regression model was employed to estimate the impact of AI adoption on economic efficiency in agricultural enterprises. The econometric specification is defined as follows:

$$EEIi = \beta 0 + \beta 1AIi + \beta 2FSi + \beta 3FOi + \beta 4LSi + \varepsilon i$$

where:

EE_i = Economic Efficiency Index;

AI_i = binary AI adoption variable;

FS_i = farm size (log-transformed hectares);

FO_i = fertilizer optimization score (standardized);
LS_i = labor skills index (based on farmer training and experience);

β_0 = intercept term;
$\beta 1, \beta 2, \beta 3, \beta 4$ = estimated regression coefficients;

$\beta_{I.}$ = error term.

Data Visualization

Results are presented using:

- comparative statistical tables,
- histograms showing distribution of yields and costs,
- bar charts comparing resource consumption,
- regression plots illustrating relationships between AI adoption and economic performance.

Research Reliability and Limitations

To ensure reliability, data validation procedures included cross-checking financial and production records with survey responses. Standardization procedures were applied to eliminate scale differences among farms.

The study acknowledges certain limitations, including regional specificity of the sample and differences in technological maturity among farms. However, the selected

dataset provides a realistic representation of agricultural enterprises undergoing digital transformation.

Results

Descriptive Statistical Analysis

The descriptive statistical analysis provides an overview of the economic and sustainability indicators observed among AI-adopting farms (Group A) and conventional farms (Group B). Table 1 presents the mean values and standard deviations for the analyzed variables.

The distribution of crop yield across farm groups is illustrated in Figure 1, showing higher average productivity among AI-adopting farms.

The results indicate higher productivity and lower resource consumption among farms implementing AI-based smart farming technologies.

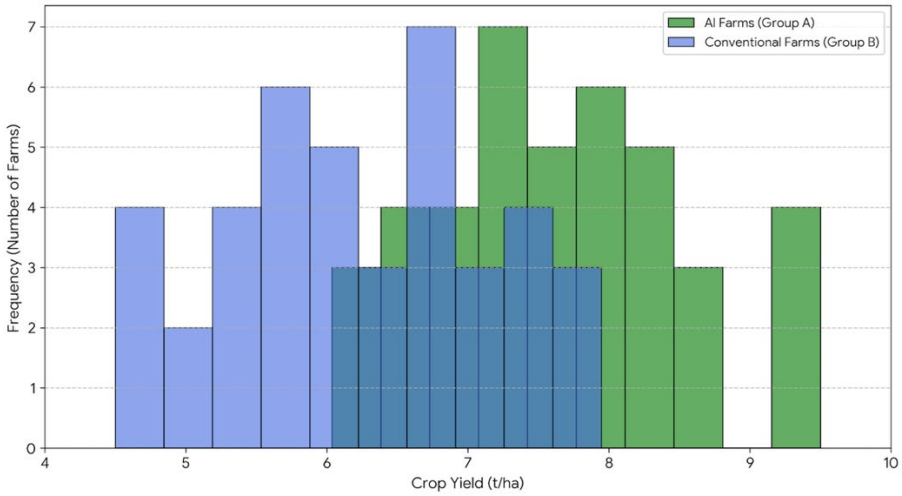
These descriptive differences highlight structural disparities typical of transitional agricultural economies, where uneven technology adoption shapes productivity outcomes. The observed patterns suggest that AI integration may function as a key mechanism supporting efficiency convergence and modernization within evolving agricultural systems.

Table 1. Descriptive statistics of analyzed variables

Indicator	Group A (AI farms) Mean	Group B (Conventional) Mean	Std. Dev. (A)	Std. Dev. (B)	Min	Max
Farm Size (ha)	85.0	85.0	42.5	45.2	15.0	250.0
Crop yield (t/ha)	7.84	6.21	0.92	1.11	4.50	9.50
Production cost (€/ha)	1,145	1,320	135	168	850	1,750
Net income (€/ha)	1,965	1,342	210	245	950	2,400
Labour productivity (€/worker)	48,200	35,600	4,320	5,010	28,000	58,000
Water consumption (m^3/ha)	2,150	2,780	260	310	1,800	3,500
Fertilizer use (kg/ha)	168	214	22	28	130	280
Energy consumption (kWh/ha)	1,020	1,340	140	175	800	1,850

Source: Prepared by authors based on statistical results

Figure 1. Distribution of Crop Yield by Farm Type



Source: Authors' processing

Comparative Analysis Between Farm Groups

An independent samples *t-test* was conducted to evaluate statistically significant differences between AI-adopting and conventional farms.

Table 2. Independent samples t-test results

Variable	Group A (AI) Mean	Group B (Conv.) Mean	t-value	p-value	Sig.
Farm Size (ha)	85.00	85.00	0.000	1.000	ns
Crop Yield (t/ha)	7.84	6.21	6.842	< 0.001	***
Production Cost (€/ha)	1,145	1,320	-4.215	< 0.01	**
Net Income (€/ha)	1,965	1,342	5.928	< 0.001	***
Water Use (m³/ha)	2,150	2,780	-7.104	< 0.001	***
Fertilizer Use (kg/ha)	168	214	-5.432	< 0.001	***

*Note: ns = not significant; p < 0.01; *** p < 0.001*

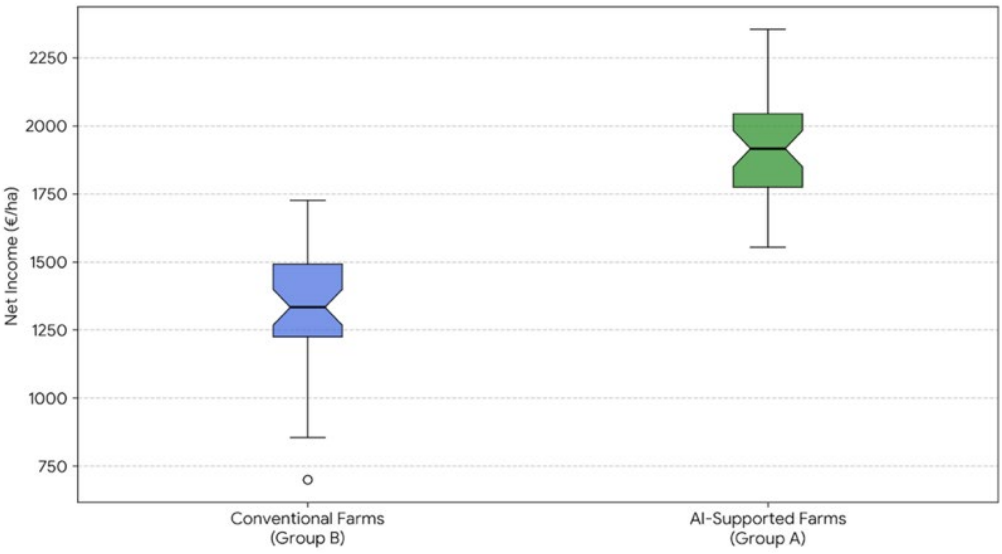
Source: Prepared by authors based on statistical results

Farm size did not differ significantly between the groups in the reported descriptive comparison; however, farm size was retained as a control variable in the regression analysis because scale-related differences may influence farm performance.

The results demonstrate statistically significant differences across all major economic and sustainability indicators, confirming measurable performance advantages among AI-adopting farms.

Figure 2 presents a box-plot analysis of net income distribution. The AI-supported group (Group A) demonstrates a clear upward shift in profitability, with a higher median income and tighter distribution compared to Group B, reflecting the economic stability provided by smart management tools.

Figure 2. Economic Performance Comparison: Net Income per Hectare



Source: Authors' processing

Correlation Analysis

Pearson correlation coefficients were calculated to examine relationships between AI adoption and farm performance indicators.

Table 3. Correlation matrix (selected variables)

Variable	AI Adoption	Farm Size	Yield	Net Income	Water Use
AI Adoption	1.00	0.04	0.62**	0.68**	-0.59**
Farm Size	0.04	1.00	0.29*	0.35**	-0.15
Yield	0.62**	0.29*	1.00	0.71**	-0.41*
Net Income	0.68**	0.35**	0.71**	1.00	-0.46*
Water Use	-0.59**	-0.15	-0.41*	-0.46*	1.00

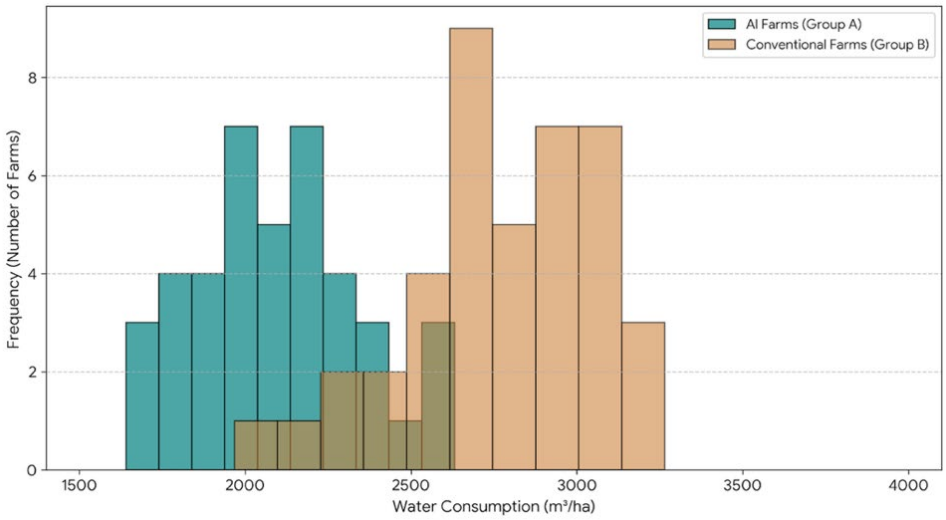
*Note: *p < 0.05; **p < 0.01;* ***p < 0.001

Source: Prepared by authors based on statistical results

AI adoption shows a strong positive correlation with yield and net income, and a negative correlation with water consumption, indicating improved resource efficiency. The correlation between AI adoption and farm size is negligible (r = 0.04, not significant), consistent with the stratified sampling design and with the t-test result reported in Table 2, which found no significant difference in average farm size between the two groups.

Figure 3 demonstrates reduced variability and lower average water consumption in technologically advanced farms.

Figure 3. Water Consumption Distribution by Farm Type



Source: Authors' processing

Regression Analysis

To further investigate the determinants of digital transformation success, a multiple linear regression analysis was conducted. The results, presented in Table 4, evaluate the impact of various technological and structural factors on the overall economic performance of the surveyed farms.

Table 4. Multiple Linear Regression Results

(Dependent Variable: Economic Efficiency Index)

Predictor Variables	Coefficient (β)	Std. Error	t-stat	p-value	Sig.
(Constant)	0.412	0.085	4.847	< 0.001	***
AI Adoption (Dummy)	0.584	0.062	9.419	< 0.001	***
Farm Size (log ha)	0.215	0.045	4.777	< 0.001	***
Fertilizer Optimization	0.142	0.051	2.784	0.007	**
Labour Skills	0.098	0.048	2.041	0.045	*
R-squared	0.742				
Adjusted R-squared	0.728				
F-statistic	52.14				***

*Note: * $p < 0.05$; $p < 0.01$; *** $p < 0.001$*

Source: Prepared by authors based on statistical results

The EEI, serving as the dependent variable, was constructed as a composite normalized score ranging from 0 to 1. The index integrates four dimensions of farm-level economic performance: crop yield, net farm income, labour productivity, and production cost. Yield, net income, and labour productivity enter the index positively, whereas

production cost enters negatively, reflecting its inverse relationship with economic efficiency. The sustainability-related indicators, including water and fertilizer use, were analysed separately and were not incorporated into the EEI.

The regression model demonstrates a high explanatory power, with an Adjusted R-squared of 0.728, indicating that approximately 73% of the variance in economic efficiency is explained by the included predictors. The F-statistic (52.14, $p < 0.001$) confirms the overall statistical significance of the model.

Key findings from the regression analysis include:

AI Adoption ($\beta = 0.584$, $p < 0.001$): This remains the strongest predictor of economic efficiency. Farms that have integrated AI-driven decision support systems show a significantly higher efficiency index, confirming that technology is the primary driver of performance in the sample.

Farm Size ($\beta = 0.215$, $p < 0.001$): Farm size exhibits a positive and statistically significant association with the Economic Efficiency Index. This result indicates that larger holdings within the observed 15–250 ha range tend to have higher efficiency scores. However, farm size was retained as a control variable because scale-related differences may contribute to observed performance differences. Therefore, the regression result should not be interpreted as evidence that the estimated association between AI adoption and economic efficiency is independent of farm size.

Fertilizer Optimization ($\beta = 0.142$, $p = 0.007$): The significant positive coefficient highlights the economic importance of sustainable resource management within the Industry 5.0 framework.

Labour Skills ($\beta = 0.098$, $p = 0.045$): The human-centric aspect of the model is validated by the positive impact of operator skills, although its influence is secondary to the technological variables.

These results provide empirical evidence that while scale (farm size) plays a role, the strategic adoption of artificial intelligence is the most critical factor for driving economic efficiency and sustainable development in modern agriculture.

Figure 4 illustrates the predictive accuracy of the multiple linear regression model by comparing the actual observed values of the EEI against the values predicted by the model.

The clustering of data points along the 45-degree reference line (Perfect Fit) demonstrates a strong correlation between the variables, confirming the model's high reliability.

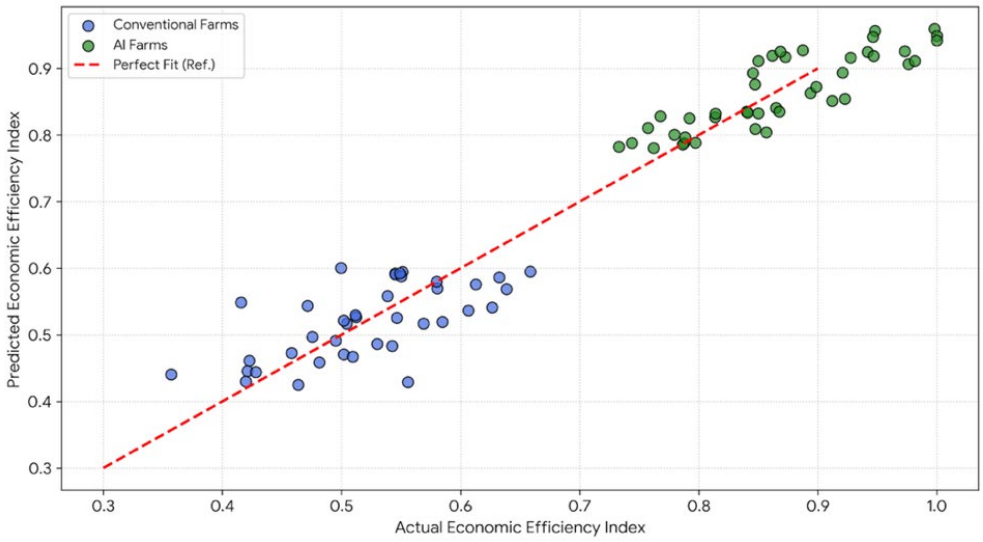
Group Differentiation: The green markers (AI-supported farms) are predominantly located in the upper-right quadrant, representing high efficiency levels. Conversely, the blue markers (conventional farms) are clustered in the lower-left quadrant, indicating lower efficiency scores.

Model Consistency: The regression specification reported in Table 4 includes AI

adoption, farm size, fertilizer optimization, and labour skills as predictors of the Economic Efficiency Index.

This diagnostic visualization confirms that the regression equation provided in Table 4 accurately captures the underlying patterns of digital transformation impacts within the transition economy context.

Figure 4. Regression Model Validation: Predicted vs Actual EEI



Source: Authors' processing

Distribution Analysis

Histogram analysis reveals structural differences between the two farm groups:

- AI-adopting farms demonstrate a normal distribution with higher mean yield values.
- Conventional farms show wider variability and lower median productivity.
- Resource consumption distributions are more compact among AI farms, indicating operational optimization.

Yield distribution analysis shows that 78% of AI farms achieve yields above 7 t/ha, compared to only 34% of conventional farms.

Summary of Key Findings

The empirical results indicate that:

- AI adoption significantly increases crop yield and net farm income.
- Production costs per hectare decrease despite initial technology investments.

- Labour productivity improves substantially in digitally supported farms.
- Water, fertilizer, and energy consumption are significantly reduced.
- AI-supported decision-making contributes to measurable improvements in economic efficiency.

Discussion

Interpretation of Key Findings

The results of this study confirm that AI and smart farming technologies significantly improve economic efficiency and sustainability in modern agriculture. Beyond validating existing assumptions about smart farming benefits, this research provides empirical evidence from a transitional agricultural context—the Republic of Serbia—where quantitative assessments of AI-driven efficiency have remained limited. The findings demonstrate measurable improvements in production performance, cost optimization, and environmental resource management, supporting the view that digital transformation represents a key driver of agricultural modernization.

The increase in crop yield among AI-adopting farms indicates that data-driven decision-making enhances production precision and operational planning. AI-supported systems optimize irrigation, fertilizer application, and pest management, reducing inefficiencies commonly associated with conventional farming practices. The positive relationship between AI adoption and productivity further suggests that predictive analytics helps mitigate uncertainty related to climate variability.

Cost reductions observed in the results highlight the economic advantages of automation and intelligent monitoring systems. Lower expenditures on water, fertilizers, and energy confirm improved resource allocation efficiency, aligning with agricultural economic theories that emphasize productivity growth through technological innovation. Importantly, improved sustainability indicators demonstrate that technological adoption can simultaneously enhance productivity and environmental performance, supporting the concept of sustainable intensification.

Comparison with Existing Literature

The findings are consistent with previous studies showing that AI-based decision-support tools enhance farm management efficiency and reduce operational risks (Idoje et al., 2021), while AI-driven analytics improves productivity through automation and real-time data processing (Walter et al., 2017). Similarly, the results support conclusions that AI technologies generate value primarily through optimization rather than expansion of production inputs (Ignjatović et al., 2025) and contribute to balancing economic and environmental objectives (Raj & Prahadeeswaran, 2025).

Compared with earlier research focused mainly on technological performance, this study contributes additional insight by quantitatively linking AI adoption with economic indicators relevant to farm profitability and agricultural policy. From an

agricultural economics perspective, AI adoption enhances farm competitiveness by increasing productivity while reducing operational costs—a finding particularly relevant for transitional and developing agricultural economies characterized by persistent efficiency gaps.

Policy and Practical Implications

Policy measures supporting digital infrastructure, farmer education, and investment incentives may accelerate technology adoption and strengthen sustainable rural development. AI-driven agriculture may also reshape labor demand toward digitally skilled workers, requiring adjustments in agricultural education and workforce development strategies. The findings provide a foundation for future longitudinal and cross-country analyses examining how digital technology adoption reshapes productivity dynamics and sustainability outcomes over time.

Limitations of the Study

Several limitations should be acknowledged. First, the cross-sectional design captures AI adoption and farm performance at a single point in time, preventing causal inference. While statistical controls were included to account for observable farm characteristics, unobserved confounding factors—such as farmer motivation, management quality, or access to technical support—may still influence both adoption decisions and performance outcomes. Therefore, the observed associations should be interpreted as correlational rather than causal. Longitudinal panel designs tracking farms before and after AI adoption would be necessary to establish causal effects with greater confidence.

Directions for Future Research

Future studies should address these limitations through: (1) longitudinal panel designs tracking AI effects over 5-10 years; (2) cross-country comparative analyses across Southeast Europe to identify contextual moderators; (3) randomized controlled trials isolating specific AI applications (e.g., irrigation vs. fertilization algorithms); (4) mixed-methods research incorporating farmer perceptions, barriers to adoption, and behavioral factors; (5) cost-benefit analyses of AI investment thresholds for small versus large farms; and (6) examination of AI's labor displacement and skill-upgrading effects on agricultural employment.

Conclusions

Theoretical, Practical, and Managerial Implications

Theoretical implications. This study extends agricultural economics theory by demonstrating that AI adoption functions as a factor-augmenting technological change, increasing the marginal productivity of land, labor, water, and energy simultaneously. Findings support the sustainable intensification framework, showing that productivity gains and environmental improvements are complementary rather than competing objectives in digitalized agricultural systems. The study also contributes to technology

diffusion theory by quantifying adoption gaps in transitional economies, revealing that the digital divide in agriculture manifests not only in access to technology but also in the capacity to derive economic benefits from it. Furthermore, the results challenge the conventional assumption that small farms face insurmountable barriers to AI adoption, demonstrating that cloud-based and software-as-a-service models can generate positive returns even on medium-sized holdings (15-250 hectares).

Practical implications for farm managers. The empirical results indicate that AI adoption is associated with lower production costs and higher net farm income. Based on the group means reported in Table 1, production costs are approximately 13.3% lower among AI-adopting farms (€175 per hectare on average), while net farm income is approximately 46.4% higher. These differences suggest potentially favourable economic conditions for technology adoption; however, a formal payback period cannot be established from the present analysis because the study does not include a farm-level investment cash-flow assessment. Farm managers should therefore evaluate technology adoption according to farm size, initial investment requirements, expected operating savings, and local production conditions. For smaller farms (below 50 hectares), cloud-based AI services delivered through mobile platforms offer lower entry barriers than full hardware integration, enabling gradual adoption without substantial upfront capital expenditure. Managers should also invest in basic digital literacy training for staff, as the effectiveness of AI decision-support tools depends on users' ability to interpret and act upon algorithmic recommendations.

Managerial and organizational implications. Beyond individual farm management, the findings have implications for agricultural cooperatives, extension services, and agribusiness organizations. Cooperative models that share AI infrastructure and data analytics costs across multiple member farms can reduce per-farm investment burdens while maintaining access to precision farming benefits. Agricultural extension services should integrate digital advisory components into their traditional portfolios, training extension officers to support farmers in AI system selection, implementation, and troubleshooting. Agribusiness firms supplying inputs or purchasing outputs should consider offering AI decision-support tools as value-added services to strengthen farmer relationships and improve supply chain predictability.

Policy implications. Policymakers aiming to accelerate AI adoption in transitional agricultural systems should consider four priority actions. First, subsidize AI technology trials on demonstration farms to reduce perceived risk and generate locally relevant evidence. Second, invest in rural broadband infrastructure, identified as the primary adoption barrier in Serbia and similar contexts. Third, integrate digital competencies into agricultural extension services and vocational training programs. Fourth, create innovation vouchers or matching grants that enable smallholder access to AI advisory platforms, ensuring that digital transformation benefits are distributed equitably across farm size classes rather than concentrating among large enterprises.

Summary of Key Findings

This study demonstrates that AI-driven decision-support tools significantly enhance farm performance by increasing productivity, optimizing resources, and reducing operational costs. The findings confirm that digital transformation is not merely a technological shift but an economically viable pathway toward sustainable agricultural development. Empirical evidence shows that AI adoption leads to higher yields and superior input efficiency compared to conventional systems, enabling better responses to environmental and market volatility. Consequently, economic gains are directly coupled with reduced environmental pressure, specifically through optimized water and fertilizer use. These results provide robust quantitative evidence linking digital innovation with both microeconomic efficiency and macro-level sustainability.

Concluding Remarks

To maximize the benefits of AI in agriculture, coordinated action among stakeholders is essential. Policymakers must prioritize investment in rural digital infrastructure to overcome current barriers to adoption. Financial instruments, such as targeted subsidies and innovation grants, should be designed to ensure inclusive modernization for small and medium-sized farms. Furthermore, enhancing farmers' digital competencies through capacity-building initiatives is essential for long-term competitiveness. While this study is limited by its sample size and timeframe, it highlights the need for future longitudinal research across diverse regions. Ultimately, the successful integration of AI in agriculture requires coordinated action among researchers, policymakers, technology providers, and farming communities to foster resilient food systems and sustainable rural economies.

Conflict of interests

The authors declare no conflict of interest.

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DETERMINANTS OF PROFITABILITY OF AGRICULTURAL SMES IN VOJVODINA: THE ROLE OF ECO-EFFICIENCY AND CIRCULAR ECONOMY INDICATOR

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ABSTRACT

This study examines the determinants of profitability of small and medium-sized agricultural enterprises (SMEs) in Vojvodina during 2014–2023 using a balanced panel of 269 enterprises. The research tests the hypothesis that the circular economy indicator, measured as agricultural emissions intensity relative to gross value added, has a statistically significant effect on firm profitability. Profitability is measured by return on assets (ROA), while firm size, indebtedness, operational efficiency, liquidity, and asset tangibility are included as control variables. The empirical analysis is based on a fixed-effects panel regression with Driscoll–Kraay standard errors, while a two-step System GMM estimator is employed to assess robustness. The results confirm the research hypothesis, indicating that the circular economy indicator significantly affects profitability. The findings contribute to the literature by integrating a sector-level eco-efficiency indicator into a firm-level profitability model and provide implications for policies supporting the transition toward more sustainable agricultural production.

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Introduction

Agricultural production, as one of the central drivers of the primary sector, is of strategic importance for the economic system of the Republic of Serbia (Tekić et al., 2022). In this context, agriculture has multiple roles: it ensures food production and contributes to food security, affects employment and living standards in rural areas, contributes to exports, and supports overall regional development. Beyond its direct economic effects, agriculture also has broader social importance by preserving rural communities, sustaining populations in rural settlements, and preserving traditional and cultural identity. The importance of the sector is also reflected in employment data: according to the Serbian Business Registers Agency (SBRA), agricultural companies in the Autonomous Province of Vojvodina employed 14,786 workers in 2023 (SBRA, 2023). Within Serbia, Vojvodina stands out as a key agricultural region, with a solid productive capacity, favorable agro-ecological conditions, and a large number of agricultural enterprises. Vržina and Dimitrijević (2020) further emphasize the importance of Vojvodina as the central agricultural region in Serbia, noting that more than 53% of enterprises in the agriculture, forestry, and fishing sector are registered in Vojvodina. Therefore, the performance of agricultural enterprises in Vojvodina is important not only for the region itself, but also for the overall stability and competitiveness of Serbian agriculture.

However, agricultural business activity is subject to specific constraints and risks: pronounced seasonality, slower capital turnover, dependence on natural factors and weather conditions, and substantial exposure to volatility in input and output prices, while the sector is also strongly shaped by agricultural policy and subsidy systems (Dašić et al., 2022). In such an environment, business results may fluctuate considerably across years, and individual shocks (e.g., droughts, floods, diseases, increases in energy or fertilizer prices) can quickly jeopardize liquidity and profitability. Moreover, agriculture has a pronounced macroeconomic and social relevance in Serbia through its contribution to GDP, employment, and rural development, as well as by reducing the need for food imports and supporting economic stability in rural communities (SORS, 2023; Volk et al., 2014). The economic environment in Serbia is also characterized by a specific transition path, marked by a prolonged period of privatization and restructuring in the early 2000s. Between approximately 2001 and 2007, a large share of formerly state-owned enterprises and agricultural cooperatives were transferred into private hands, often under weak institutional frameworks and fragmented ownership structures. This process contributed to persistent uncertainty, fragmented land holdings, and underdeveloped support systems for small and medium enterprises, including those in agriculture. As a result, many agri-SMEs in Vojvodina inherited outdated infrastructure, limited access to capital, and relatively low managerial capacity, which constrained their investment in efficiency-enhancing technologies. These structural legacies may have indirectly slowed the adoption of eco-efficiency practices and circular-economy-oriented resource management, which in turn could affect profitability. For these reasons, the need for systematic monitoring of profitability

and financial sustainability is particularly pronounced among small and medium-sized enterprises (SMEs), which typically have smaller financial buffers, limited access to long-term financing, and more difficulty obtaining the investment capital necessary for technological upgrading. In practice, SMEs serve as a key structural component of regional agribusiness through production volumes, processing capacities, and their role in local supply chains; therefore, understanding the determinants of their profitability is crucial for designing effective development measures. Although previous studies have extensively examined the financial determinants of agricultural enterprises' profitability, empirical evidence concerning the relationship between circular economy indicators and the profitability of agricultural SMEs remains limited, particularly in Serbia. To address this research gap, the present study examines agricultural SMEs operating in Vojvodina during the period 2014–2023. Its objective is to determine whether the circular economy indicator, operationalised as the emissions intensity of agricultural production, affects profitability measured by return on assets, while controlling for firm size, indebtedness, operational efficiency, liquidity, and asset tangibility. Accordingly, the following research hypothesis is formulated:

H1: The circular economy indicator has a statistically significant effect on the profitability of agricultural SMEs in Vojvodina.

Literature review

Profitability is widely regarded as a fundamental indicator of business success and sustainability (Novaković et al., 2025). The literature emphasizes that profitability results from the simultaneous influence of multiple internal and external factors, most commonly financial structure (indebtedness/leverage), liquidity, firm size, efficiency of asset use, and asset structure (tangibility/capital intensity). Numerous international studies in the field of agriculture highlight the relevance of these determinants: Suardi and Noor (2015) find that capital-structure indicators may negatively affect profitability; Jacob and Collins (2016) report a positive impact of liquidity and firm size, while tangibility may have a negative effect; Shamsuddin et al. (2017) confirm that a combination of liquidity, asset turnover, and firm size shapes cooperatives' financial performance. Evidence for U.S. cooperatives further suggests that revenue growth can be a key positive factor, whereas uncertainty and capital intensity may negatively affect profitability (Singh et al., 2019). Similarly, Xu et al. (2021) show that leverage and short-term indebtedness negatively influence the profitability of agricultural enterprises, while firm size and sales (i.e., sales growth/efficiency) are among the factors with a stable positive effect.

Within the domestic literature, the findings are mostly consistent with international studies while preserving sensitivity to region-specific characteristics. For medium and large agricultural enterprises in Vojvodina, Andrašić et al. (2018) show that profitability (ROA) is significantly associated with internal financial and market factors (e.g., liquidity, leverage, market share, revenue growth), as well as with factors such as insurance and exports. For the Republic of Serbia, Milašinović and Mitrović (2020)

identify total asset efficiency as a key positive determinant of profitability, while certain capital-structure indicators may act as constraints. Additionally, Mutavdžić et al. (2021) confirm that indebtedness can negatively affect profitability, whereas turnover/productivity indicators may improve it. In recent panel analyses for Serbia, Tekić et al. (2022) and Novaković et al. (2025) confirm that microeconomic indicators such as indebtedness, asset turnover, liquidity, and tangibility, along with selected macroeconomic controls, represent relevant determinants of profitability in the agri-food sector. The reviewed literature provides a sound basis for the inclusion of selected variables and justifies the use of a panel approach to analyze the profitability determinants of agricultural SMEs in Vojvodina.

Simultaneously, the assessment of agricultural performance is becoming more closely framed by sustainability considerations and environmental constraints. Modern agribusiness faces growing pressure to reduce negative environmental impacts, including pollutant emissions, land degradation, water eutrophication, and biodiversity loss (Silvestri et al., 2022). In this context, the circular economy (CE) has become an increasingly important framework for transforming production systems toward greater sustainability (Silvestri et al., 2022; Xia & Ruan, 2020). In agriculture, the circular economy is commonly associated with closing material and energy loops, reducing waste, improving resource management, and lowering emission intensity (Silvestri et al., 2022; Xia & Ruan, 2020). The key idea is that equal or greater economic value can be achieved with lower environmental costs, which is often operationalized through eco-efficiency and the use of indicators that link economic and environmental dimensions (Silvestri et al., 2022; Stevanović et al., 2025).

Nevertheless, the relationship between circularity (i.e., eco-efficiency) and profitability lacks complete clarity. Improving eco-efficiency can increase competitiveness through input savings, reduced losses, process optimization, and higher resource productivity, yet the transition to circular practices may require additional investment, technological change, organizational adjustments, and compliance costs (Silvestri et al., 2022; Xia & Ruan, 2020). Therefore, in the short run, higher profitability may be associated with more intensive production patterns that increase environmental pressure, indicating a possible trade-off between profitability and environmental performance. This issue is especially relevant for SMEs, which often lack sufficient capital and knowledge to rapidly adopt cleaner technologies and circular business models without external support (Xia & Ruan, 2020). On the other hand, empirical evidence suggests that adopting CE principles can lead to better financial outcomes in rural settings and that CE firms may achieve higher profitability and resilience than comparable non-CE firms (Serrano Magdalena et al., 2025).

Although interest in circular economy and sustainability in agriculture is increasing, empirical evidence directly linking circularity indicators to firm profitability remains limited, particularly in Serbia (Novaković et al., 2026). One key reason is the lack of firm-level environmental performance data for large samples of SMEs; therefore, studies often rely on sectoral or macro indicators that describe the environmental “context” in

which firms operate (Novaković et al., 2025; Novaković et al., 2026). Such an approach enables the inclusion of environmental intensity in profitability models even when firm-level emission data are unavailable, but it requires careful interpretation because the indicator reflects sector-level changes over time rather than differences between firms within the same year (Stevanović et al., 2025; Novaković et al., 2026).

Considering the aforementioned, the subject of this study is agricultural SMEs in Vojvodina that operated from 2014–2023. The objective is to empirically determine the extent to which the circular economy indicator (CE), operationalised as emission intensity in agriculture (emissions/GVA), as well as selected internal firm indicators-size, indebtedness, operational efficiency (asset turnover), liquidity, and asset tangibility-affect profitability measured by ROA. In this way, the study aims to provide reliable empirical evidence on the "profitability–environment" relationship among agricultural SMEs in Vojvodina and to offer a basis for policy recommendations that can improve business performance while supporting the transition toward a circular economy.

Materials and methods

The analysis focuses on agricultural small and medium-sized enterprises (SMEs) operating in the Autonomous Province of Vojvodina (Serbia). According to the Serbian Business Registers Agency (SBRA, 2023), by the end of 2023, there were 374 small and 89 medium-sized agricultural enterprises operating in Vojvodina. Firm-level financial data were obtained from the annual financial statements reported to the SBRA (2026).

To construct a consistent panel suitable for econometric analysis, the initial sample was filtered in several steps. First, enterprises that did not operate continuously during 2014–2023 were excluded to ensure comparability. Second, companies with extreme ROA values were removed to reduce the influence of outliers and atypical accounting patterns on regression results. Once the data had been cleaned, the final sample consisted of 269 agricultural SMEs observed over the period 2014–2023.

The study combines firm-level financial indicators with a sector-level circular economy indicator to examine profitability determinants among agricultural SMEs in Vojvodina (Table 1). The dependent variable was return on assets (ROA), which captures firm profitability and it was calculated as net profit divided by total assets (reported in decimal form). The set of explanatory variables includes standard enterprise characteristics frequently used in profitability models: firm size (SIZE), the indebtedness ratio (DEBT), operational efficiency measured by asset turnover (OEFF), the liquidity ratio (LIQ), and asset tangibility (TANG).

Table 1. Descriptive statistics for applied models in agricultural companies

Variable	Description	Unit of analysis	Expected sign
ROA	Net profit/ average total assets	Firm level	—
SIZE	ln(total assets)	Firm level	+ / −
DEBT	Total liabilities/total assets	Firm level	−

Variable	Description	Unit of analysis	Expected sign
OEFF	Operating revenues/average total assets	Firm level	+
LIQ	Current assets/Current liabilities	Firm level	+ / −
TANG	Fixed assets/total assets	Firm level	+ / −
CE	Total air pollutant emissions in agriculture/ agricultural GVA	Year/sector level	±

Source: Authors' calculations.

Firm size is included to control for scale effects in performance, while the indebtedness ratio reflects the firm's financing structure and the potential burden of liabilities on profitability. Operational efficiency (asset turnover) captures a firm's ability to generate revenue from its asset base, and the liquidity ratio reflects working capital conditions that may support or constrain day-to-day operations. Asset tangibility measures the degree of capital intensity and may influence profitability through fixed costs, depreciation, and the utilization of tangible assets. The key explanatory variable is the circular economy indicator (CE), constructed as air pollutant emissions in agriculture relative to agricultural gross value added (emissions/GVA). Emission data were taken from the online database of the Statistical Office of the Republic of Serbia for activity KD2010: 01 (Agricultural production, hunting and related service activities) and include nitrogen oxides (NOx)**,** non-methane volatile organic compounds (NMVOC), sulphur dioxide (SO_2), particulate matter $PM_{2.5}$ and PM_{10}, carbon monoxide (CO), and ammonia (NH_3)(SORS, 2023). In line with the ratio-based eco-efficiency logic used in environmental-efficiency analyses of Serbian agricultural enterprises (Stevanović et al., 2025), CE is interpreted as an emissions-intensity measure: higher CE values indicate lower eco-efficiency, i.e., higher environmental intensity per unit of value created. Since firm-level emission data are not available, CE is measured at the sector-year level and assigned uniformly to all firms within the same year. This approach treats the environmental intensity of agricultural production as a contextual factor affecting firms operating under the same institutional, technological, and regulatory environment.

The empirical strategy combines descriptive statistics and panel econometric methods to identify the determinants of profitability and assess the role of circular economy performance among agricultural SMEs in Vojvodina. First, descriptive statistics were computed to summarize the dataset and to detect heterogeneity and potential outliers typical of accounting-based firm data (Gujarati & Porter, 2009). Next, Pearson correlation coefficients were calculated to provide an initial view of linear associations among variables, while multicollinearity was formally assessed using variance inflation factors (VIF) and tolerance values (TOL = 1/VIF).

Before estimating the main models, we tested key panel-data assumptions and selected an appropriate inference strategy. Heteroskedasticity was examined using the Breusch–Pagan approach (Breusch & Pagan, 1979). Serial correlation was assessed using Wooldridge's test for autocorrelation in fixed-effects panels (Wooldridge, 2010), complemented by Breusch–Godfrey checks in pooled specifications (Breusch, 1978;

Godfrey, 1978). Cross-sectional dependence was evaluated using Pesaran's CD test (Pesaran, 2004). Since the diagnostics indicated heteroskedasticity, serial correlation, and strong cross-sectional dependence, coefficient inference based on conventional standard errors would be unreliable. Therefore, the baseline results are reported within a fixed-effects framework using Driscoll–Kraay standard errors, which are robust to heteroskedasticity, autocorrelation, and general forms of cross-sectional dependence in panels (Driscoll & Kraay, 1998; Baltagi, 2021).

To reduce the risk of spurious regression, the stationarity properties of the variables were also examined. Because the time dimension is relatively short (T = 10) and standard panel unit-root routines proved unstable in our computing environment, we applied a Fisher-type procedure that combines firm-level ADF tests (panel Fisher-ADF) (Maddala & Wu, 1999; Choi, 2001). Individual ADF p-values were obtained via Monte Carlo simulation under the unit-root null with the same sample length and lag specification. Overall, the results supported predominantly level estimation.

The baseline profitability model is specified as:

$$ROA_{it} = \alpha + \beta_1 SIZE_{it-1} + \beta_2 DEBT_{it} + \beta_3 OEFF_{it} + \beta_4 LIQ_{it} + \beta_5 TANG_t + \beta_6 CE_t + \varepsilon_{it}$$

where ROAit denotes return on assets of firm i in year t, *CEt* is the sector-level circular economy indicator, and ε_{it} $^{\varepsilon_{it}}$ is the idiosyncratic error term. The choice between fixed-effects and random-effects estimators was guided by the Hausman test (Hausman, 1978), which favored fixed effects.

As an additional robustness check addressing dynamic persistence in profitability and potential endogeneity of firm-level regressors, we estimated a two-step System GMM model (Arellano & Bond, 1991; Blundell & Bond, 1998). To mitigate instrument proliferation, we employed a restricted instrument strategy with collapsed instruments and limited lag depth (Roodman, 2009). Model adequacy was evaluated using the Arellano–Bond AR(1) and AR(2) tests for serial correlation in differenced residuals (with AR(2) expected to be insignificant) and the Sargan test of overidentifying restrictions, interpreted cautiously given its sensitivity under heteroskedasticity and dependence structures (Baltagi, 2021; Roodman, 2009). All analyses were performed in software package R 4.5.2.

Results

Table 2 reports descriptive statistics for the variables used in the empirical analysis. The dataset contains 2,690 firm–year observations for agricultural small and medium-sized enterprises in Vojvodina over the period 2014–2023.

Table 2. Descriptive statistics

Variable	Mean	Median	Min	Max	SD	Q1	Q3
ROA	0.026	0.022	-9.111	2.524	0.194	0.006	0.052
SIZE	5.487	5.464	0.845	7.007	0.627	5.018	5.939
DEBT	0.500	0.473	0.000	32.71	0.708	0.213	0.732
OEFF	0.296	0.157	0.000	9.209	0.489	0.042	0.369
LIQ	1.071	1.460	0.000	6.630	0.723	1.030	2.800
TANG	0.454	0.458	0.000	1.000	0.269	0.237	0.678
CE	0.143	0.143	0.086	0.189	0.032	0.118	0.173

Source: Authors' calculations

Over the period 2014–2023, the average profitability of agricultural SMEs in Vojvodina, measured by ROA, is 0.026, which corresponds to approximately 2.62% (ROA is reported in decimal form). The range of ROA is wide (from −9.111 to 2.524), indicating substantial differences in business performance across firms and the presence of extreme values in certain years. Firm size (SIZE) has an average value of 5.4871, and its variation suggests that the sample includes both smaller and medium-sized enterprises with different scales of operation. The financial structure, measured by the indebtedness indicator (DEBT), averages 0.500, implying that liabilities represent an important source of financing for a typical enterprise. Operational efficiency, captured by the total business assets turnover ratio (OEFF), has a mean value of 0.296, indicating a relatively moderate level of asset turnover among agricultural firms. The liquidity ratio (LIQ) averages 1.071. Asset tangibility (TANG) averages 0.454, which is consistent with the more capital-intensive nature of agricultural production. Finally, the circular economy indicator (CE), defined as the ratio of emissions to agricultural gross value added, has an average value of 0.143 and varies over time at the sector level, reflecting changes in the environmental intensity of value creation in agriculture during the observed period.

To obtain a preliminary insight into bivariate relationships among the variables, we computed the Pearson correlation matrix reported in Table 3. This step helps to (i) describe simple associations between profitability, firm-level financial indicators, and the circular economy measure and (ii) provide an initial check for potential multicollinearity before estimating panel regression models.

Table 3. Correlation matrix

	ROA	SIZE	DEBT	OEFF	LIQ	TANG	CE
ROA	1.000	0.127	-0.833	0.046	0.013	0.000	0.024
SIZE	0.127	1.000	-0.272	-0.120	-0.023	0.529	-0.120
DEBT	-0.833	-0.272	1.000	-0.026	-0.031	-0.242	0.015
OEFF	0.046	-0.120	-0.026	1.000	-0.015	-0.005	0.028
LIQ	0.013	-0.023	-0.031	-0.015	1.000	-0.028	-0.007
TANG	0.000	0.529	-0.242	-0.005	-0.028	1.000	-0.051
CE	0.024	-0.120	0.015	0.028	-0.007	-0.051	1.000

Source: Authors' calculations

In bivariate terms, profitability (ROA) is strongly negatively correlated with the indebtedness ratio (DEBT) (r = -0.833), indicating that more indebted firms tend to exhibit lower profitability. Given that correlation analysis reflects only pairwise associations, in the next step we formally assessed potential multicollinearity among regressors by computing variance inflation factors (VIFs) and their corresponding tolerance values (TOL = 1/VIF), reported in Table 4.

Table 4. Multicollinearity diagnostics (VIF and tolerance)

Variable	VIF	TOL (=1/VIF)
SIZE	1.457	0.686
DEBT	1.350	0.741
OEFF	1.023	0.978
LIQ	1.011	0.989
TANG	1.667	0.600
CE	1.016	0.984

Source: Authors' calculations

The results indicate no multicollinearity problems: all VIF values are low (approximately 1.01–1.67) and all tolerance values are high (0.60–0.99), suggesting that the explanatory variables are not highly correlated in a way that would distort coefficient estimates.

Before estimating the main panel regression models, we conducted a set of diagnostic tests to verify key assumptions and to determine the appropriate inference strategy. Specifically, we tested for heteroskedasticity, serial correlation, and cross-sectional dependence (Table 5).

Table 5. Diagnostic tests (heteroskedasticity, serial correlation, and cross-sectional dependence)

Test	Null hypothesis (H0)	Test statistic	p-value	Conclusion
Breusch–Pagan (heteroskedasticity)	Homoscedastic errors	BP = 7.365	0.007	Reject H0 → heteroskedasticity
Wooldridge test (serial correlation in FE)	No first-order serial correlation	F = 14.931	0.000	Reject H0 → serial correlation
Breusch–Godfrey AR(1) (pooled OLS)	No serial correlation (AR1)	LM = 72.394	<0.001	Reject H0 → serial correlation
Breusch–Godfrey AR(2) (pooled OLS)	No serial correlation (AR2)	LM = 115.926	<0.001	Reject H0 → serial correlation
Pesaran CD (cross-sectional dependence)	Cross-sectional independence	CD = 38.593	<0.001	Reject H0 → CSD present

Source: Authors' calculations

The diagnostic results indicate that the error structure deviates from the classical panel assumptions. We find evidence of heteroskedasticity, serial correlation, and strong cross-sectional dependence ($p<0.05$). In addition, we examined the stationarity properties of the variables using panel unit root tests (Table 6).

Table 6. Panel unit root tests (Fisher-ADF)

Variable	Fisher statistic	df	p-value	Stationarity inference
ROA	1225.422	538	<0.001	Stationary (I(0))
SIZE	577.386	536	0.105	Non-stationary / inconclusive
DEBT	641.732	538	0.00135	Stationary (I(0))
OEFF	1096.812	538	<0.001	Stationary (I(0))
LIQ	735.914	538	<0.001	Stationary (I(0))
TANG	689.889	536	<0.001	Stationary (I(0))

Source: Authors' calculations

Overall, the results indicate that the main variables used in the profitability model are stationary in levels. The only exception is SIZE, for which the Fisher-ADF test does not reject the unit-root null at conventional significance levels ($p = 0.105$). Given that firm size is a standard control in profitability models and is already expressed in logarithmic form, we retain SIZE in levels in the baseline specification and additionally verify robustness using alternative specifications when appropriate. CE is a sector-level (time-varying) indicator that is identical across firms within the same year; therefore, it is treated as a macro-level regressor in the panel models and cannot be jointly identified with a full set of year fixed effects.

Next, we estimated pooled OLS, fixed-effects (FE), and random-effects (RE) panel specifications to identify the appropriate estimator. The Hausman test strongly rejected the null hypothesis of RE consistency ($\chi^2(7) = 44.804$, $p = 0.000$), indicating that unobserved firm-specific effects are correlated with the regressors. Consequently, the FE framework was selected as the baseline estimator.

Given the diagnostic evidence of heteroskedasticity, serial correlation, and strong cross-sectional dependence, coefficient inference based on conventional standard errors would be unreliable. Therefore, in the subsequent analysis we report FE estimates with Driscoll–Kraay standard errors, which are robust to heteroskedasticity, autocorrelation, and cross-sectional dependence, and treat these results as the primary basis for inference. Based on the Hausman test results and the diagnostic evidence of heteroskedasticity, serial correlation, and cross-sectional dependence, the final estimates are reported using a fixed-effects specification with Driscoll–Kraay standard errors. The results of the baseline FE model are reported in Table 7.

Table 7. Fixed-effects estimates with Driscoll–Kraay standard errors (baseline specification)

Variable	Coefficient	Robust SE (DK)	t-stat	p-value
SIZE	0.0204	0.0177	1.1484	0.2509
DEBT	-0.2740	0.0141	-19.4795	<0.001
OEFF	0.0201	0.0062	3.2291	0.0013
LIQ	-0.0001	0.0000	-2.7688	0.0057
TANG	-0.0938	0.0172	-5.4632	<0.001
CE	0.2394	0.0734	3.2591	0.0011

Source: Authors' calculations

The results indicate that the circular economy indicator (CE) is positive and statistically significant, suggesting that higher environmental intensity (higher emissions per agricultural GVA) is associated with higher profitability (ROA), consistent with a short-run profit–environment trade-off. Indebtedness (DEBT) exhibits a strong negative association with profitability, while operational efficiency (OEFF) is positively related to ROA. Tangibility is negatively associated with ROA, implying that more capital-intensive firms tend to achieve lower profitability. Liquidity shows a negative and statistically significant coefficient, indicating that higher liquidity is associated with lower ROA, potentially reflecting idle resources or conservative working-capital management.

As an additional robustness check addressing potential dynamic persistence in profitability and endogeneity concerns, we estimated a two-step System GMM model. We applied a restricted instrument strategy (collapsed instruments and limited lag depth) to mitigate instrument proliferation. The results are reported in Table 8.

Table 8. Dynamic robustness: Two-step System GMM results (restricted instruments)

Variable/ Diagnostics	Coefficient	Robust SE	z-stat	p-value
lag(ROA, 1)	-0.0388	0.0045	-8.6969	<0.001
SIZE	0.0126	0.0065	1.9410	0.0523
DEBT	-0.0586	0.0328	-1.7857	0.0742
OEFF	-0.0175	0.0541	-0.3232	0.7466
LIQ	-0.0052	0.0117	-0.4464	0.6553
TANG	-0.0615	0.0257	-2.3975	0.0165
CE	0.1775	0.0436	4.0671	<0.001
Model diagnostics				
Sargan test $\chi^2(7)$	21.105	—	—	0.00362
Arellano–Bond AR(1)	—	—	—	0.000153
Arellano–Bond AR(2)	—	—	—	0.164

Source: Authors' calculations

System GMM results confirm the baseline conclusion from the fixed-effects model with Driscoll–Kraay standard errors. The circular economy indicator (CE) remains positive and highly significant, indicating that higher environmental intensity is associated with higher profitability even after accounting for dynamic effects. The AR(2) test does not reject the null of no second-order serial correlation, supporting the validity of the dynamic specification. Although the Sargan test rejects the overidentifying restrictions, this test can be sensitive under heteroskedasticity and cross-sectional dependence; therefore, the GMM estimates are interpreted primarily as robustness evidence. Overall, the stability of the CE coefficient across FE and System GMM specifications supports the robustness of the main finding.

Discussion

This study examined profitability determinants of agricultural SMEs in Vojvodina during 2014–2023, with a particular focus on whether a circular economy/eco-efficiency proxy (CE) is associated with firm profitability (ROA). The baseline fixed-effects model

with Driscoll–Kraay standard errors indicates that CE has a positive and statistically significant coefficient. These findings support the proposed research hypothesis (H1), confirming that the circular economy indicator has a statistically significant effect on the profitability of agricultural SMEs in Vojvodina. Given that higher CE values represent higher environmental intensity (lower eco-efficiency), this finding suggests that, in the observed period, higher emissions intensity at the sector-year level coincided with higher firm profitability. Substantively, the result is consistent with the idea of a short-run profit–environment trade-off, where profitability may be supported by more intensive production patterns and input use that increase environmental pressure. This interpretation fits the broader CE debate, which highlights that while eco-efficiency can improve competitiveness over longer horizons, the transition to circular practices may require investments and adjustment costs that can restrain short-run profitability.

In terms of firm-level determinants, indebtedness (DEBT) shows a strong and robust negative association with ROA in the baseline model, indicating that more indebted agricultural SMEs tend to achieve lower profitability. This result aligns with extensive empirical evidence emphasizing the negative impact of indebtedness on performance outcomes, including studies that report negative leverage effects in agricultural enterprises and cooperatives (Suardi & Noor, 2015; Xu et al., 2021; Tekić et al., 2022; Mutavdžić et al., 2021). In agriculture, this relationship can be particularly pronounced due to income volatility and seasonality, which raise the cost of servicing liabilities and increase financial vulnerability. Operational efficiency (OEFF) is positively related to profitability in the FE model, implying that firms which generate higher revenues per unit of assets tend to achieve higher ROA. This is in line with international and domestic studies that identify turnover/efficiency measures as critical drivers of profitability (Shamsuddin et al., 2017; Milašinović & Mitrović, 2020), and it also aligns with evidence for Serbian SMEs showing that turnover ratios are among the most stable positive determinants of profitability (Novaković et al., 2025; Tekić et al., 2022). The finding reinforces the managerial relevance of productivity-oriented strategies, better capacity utilization, and improved asset management. Asset tangibility (TANG) is negative and significant, suggesting that more capital-intensive companies tend to be less profitable, holding other factors constant. This outcome is consistent with findings where capital intensity or asset tangibility is associated with lower profitability, often attributed to higher fixed costs, depreciation burden, and underutilization of fixed assets (Jacob & Collins, 2016; Singh et al., 2019; Xu et al., 2021). In agricultural SMEs, high tangibility may also reflect rigid production structures and limited flexibility in adapting to shocks or market shifts, which can depress returns. Liquidity (LIQ) in the baseline model has a negative and significant coefficient. While some studies report a positive liquidity–profitability relationship in agriculture (Jacob & Collins, 2016), negative coefficients are also plausible in firm-level accounting data, particularly when high liquidity reflects idle resources, conservative working-capital policies, or weak investment opportunities rather than operational strength. In this context, the result suggests that excessive liquidity may be associated with lower profitability, highlighting

the importance of balancing solvency with efficient capital allocation. Finally, firm size (SIZE) is not statistically significant in the baseline model. This indicates that after controlling for firm fixed effects and the remaining financial indicators, scale differences within the SME segment do not systematically explain profitability. This contrasts with some studies that find size effects in agriculture (Jacob & Collins, 2016; Shamsuddin et al., 2017), but it may reflect the relatively narrow size dispersion among SMEs, as well as the dominance of firm-specific unobserved factors captured by fixed effects.

The dynamic System GMM results serve as an additional robustness check. The CE coefficient remains positive and statistically significant, supporting the stability of the main conclusion regarding the profitability–environment relationship. However, some coefficients at the company-level appear weaker and no longer retain statistical significance, which is not uncommon when dynamic specification, instrumentation, and short time dimension are considered. Importantly, while AR(2) does not indicate problematic second-order serial correlation, the rejection of the Sargan test suggests caution in interpreting the GMM estimates as definitive; therefore, the GMM results are best viewed as robustness evidence rather than the primary basis for inference.

Several limitations should be considered when interpreting the findings. First, the circular economy indicator (CE) is constructed at the sector-year level and assigned uniformly to all firms within a given year. As a result, the model captures how changes in sector-level emissions intensity over time relate to profitability, but it cannot identify differences in eco-efficiency between firms operating in the same year. Future research would benefit from firm-level environmental indicators (e.g., energy use, fertilizer intensity, waste streams, or firm-specific emissions), which would enable a clearer assessment of how eco-efficiency strategies affect profitability within the SME population. Second, the analysis focuses primarily on internal firm indicators and a CE proxy, but other relevant drivers, such as subsidies**,** insurance**,** export orientation**,** technology adoption**,** and climate risk exposure, were not explicitly modeled. Prior evidence suggests that such factors can be important in agricultural performance models (e.g., Andrašić et al., 2018). Future research could incorporate these variables and explore their effects. Third, the short time dimension (T = 10) constrains both stationarity testing and dynamic modeling. While the FE with Driscoll–Kraay standard errors provides robust inference under heteroskedasticity, serial correlation, and cross-sectional dependence, dynamic GMM results can be sensitive to instrument choice and diagnostic performance. Future work could consider alternative dynamic estimators, refined instrument, or longer time series as data become available.

Conclusions

This study examined the determinants of profitability of agricultural SMEs in Vojvodina over the period 2014–2023, with particular emphasis on the role of a circular economy indicator as a proxy for eco-efficiency. The empirical findings support the proposed research hypothesis (H1), confirming that the circular economy indicator has a statistically significant effect on the profitability of agricultural SMEs in Vojvodina. The

positive relationship between the circular economy indicator and profitability suggests the existence of a short-run trade-off between financial performance and environmental performance, indicating that higher environmental intensity was associated with higher profitability during the observed period. This finding contributes to the existing literature by extending conventional profitability models through the integration of a sector-level circular economy indicator into the analysis of agricultural SMEs. The findings also indicate that profitability is influenced by firms' financial characteristics, highlighting the importance of prudent debt management, efficient asset utilization, and balanced liquidity management for improving business performance. Rather than viewing environmental sustainability and profitability as mutually exclusive objectives, the results suggest that the transition toward more eco-efficient production may require targeted policy support that helps SMEs overcome the short-term costs of adopting cleaner technologies and circular business practices. From a policy perspective, the findings imply that accelerating the transition toward circular and eco-efficient agricultural production may require measures that lower adjustment costs for SMEs, such as targeted investment support for cleaner technologies, advisory services, and financing instruments that facilitate sustainable business transformation. For managers, the results emphasize the importance of improving operational efficiency, maintaining sustainable debt levels, optimizing asset utilization, and preparing for the gradual adoption of circular economy practices that can enhance long-term competitiveness and sustainability.

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Conflict of interests

The authors declare no conflict of interest.

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ENVIRONMENTAL DEGRADATION, ENVIRONMENTALLY INDUCED MIGRATION AND SUSTAINABLE TOURISM DEVELOPMENT IN RURAL REGIONS OF SERBIA

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ABSTRACT

Environmental degradation and population migration represent important challenges for sustainable rural development, particularly in regions characterized by limited economic opportunities and demographic decline. This study examines the relationships between environmental degradation, environmentally induced migration, and sustainable tourism development in selected rural regions of Serbia. Data were collected through a structured questionnaire administered to 212 respondents. The analysis included descriptive statistics, reliability analysis, exploratory factor analysis, correlation analysis, and multiple linear regression. The results indicate strong associations between perceived environmental degradation, reduced quality of life and socio-economic security, environmentally induced migration, and negative demographic change. Environmental degradation and migration were also strongly associated with perceived constraints on sustainable tourism development. The findings highlight the interconnected nature of environmental, demographic, and economic processes and support the need for integrated rural development policies combining environmental protection, demographic stability, and sustainable tourism development.

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Introduction

Environmental degradation has become one of the most significant challenges to sustainable economic and regional development, particularly in rural and peripheral areas where livelihoods and local economic activities remain strongly dependent on the availability and quality of natural resources. Processes such as soil degradation, water and air pollution, deforestation, biodiversity loss, and the deterioration of ecosystem services can directly affect agricultural production, employment opportunities, human well-being, and the overall quality of life of local populations (FAO, 2018; IPCC, 2022).

Consequently, environmental degradation can no longer be regarded exclusively as an ecological problem, but rather as a multidimensional development challenge with pronounced economic, social, spatial, and demographic consequences. The effects of environmental degradation are particularly important in rural regions, where economic structures are often less diversified and local communities are more dependent on agriculture, natural resources, and ecosystem services. Environmental pressures may therefore intensify existing structural disadvantages, reduce livelihood security, and limit the capacity of local economies to generate stable employment and income. From the perspective of sustainable livelihoods, deterioration of the natural resource base increases household vulnerability and may encourage the adoption of alternative livelihood strategies, including migration (Scoones, 2015).

A growing body of migration research recognizes environmental change as an important factor influencing population mobility. Environmental degradation can operate as a push factor which, in interaction with economic vulnerability, limited employment opportunities, institutional conditions, and individual household characteristics, contributes to migration decisions (Black et al., 2011; McLeman, 2018; Piguet et al., 2011). Environmentally induced migration should not, however, be interpreted as a simple or deterministic response to environmental change. Migration decisions generally emerge from the interaction of environmental, economic, social, and institutional pressures, while the importance of each factor varies according to the vulnerability and adaptive capacity of particular communities (McLeman & Smit, 2006; Hugo, 2014).

Migration can consequently be understood both as a response to environmental and socioeconomic pressures and as an adaptation strategy through which individuals and households attempt to reduce risk and improve livelihood security (Black et al., 2011; Tacoli, 2009). The departure of younger and economically active residents can accelerate population ageing, reduce the available labour force, weaken local entrepreneurship, and diminish the human and social capital necessary for regional development (Castles, 2010; Johnson & Lichter, 2019). These effects are particularly important in rural and peripheral areas already affected by depopulation and limited economic diversification.

Within this context, tourism represents a potentially important mechanism for diversifying rural economies and creating alternative sources of employment and income. Rural areas frequently possess natural landscapes, biodiversity, cultural heritage, traditional production systems, and local identities that can provide a basis

for tourism development. Sustainable tourism may therefore contribute to local economic diversification, support small businesses and entrepreneurship, generate employment opportunities, and strengthen the economic viability of rural communities (Hall & Williams, 2019; Rosalina et al., 2021; López-Sanz et al., 2021). At the same time, however, tourism is strongly dependent on environmental quality, landscape preservation, infrastructure, and the availability and participation of the local population (Hall & Williams, 2019; UNWTO, 2018).

The relationship between environmental conditions and tourism is therefore bidirectional. Tourism development can generate economic opportunities and contribute to the revitalization of local communities, but poorly planned tourism may simultaneously increase pressure on natural resources and contribute to environmental degradation (Hall, 2019; Li et al., 2024). Sustainable tourism requires an appropriate balance between economic benefits, environmental protection, and the social interests of host communities (Hall, 2019). Environmental deterioration may reduce destination attractiveness and negatively influence tourists' perceptions and behavioural intentions, while environmental and natural hazards may significantly affect destination choice and willingness to travel. Evidence from Serbian tourists, for example, indicates that perceived earthquake hazards can influence willingness to visit a destination, demonstrating the broader importance of environmental risk perceptions in tourism decision-making (Blešić et al., 2024).

Population migration adds another dimension to this relationship, as continued outmigration may reduce the local labour force, entrepreneurial capacity, and community participation necessary for sustainable tourism development. Conversely, tourismrelated employment and economic opportunities may contribute to local diversification and potentially reduce some migration pressures, particularly in rural and depopulating areas (López-Sanz et al., 2021; Rosalina et al., 2021).

The concept of sustainable development emphasizes the interdependence of environmental, economic, and social dimensions (WCED, 1987; Sachs, 2015). Applied to rural regions, this perspective requires environmental degradation, population dynamics, and tourism development to be considered as interconnected components of long-term regional sustainability.

The Republic of Serbia provides a relevant context for examining these relationships. Numerous rural and peripheral areas of the country are characterized by demographic decline, population ageing, migration of younger residents, limited economic diversification, and varying forms of environmental pressure. At the same time, many of these areas possess valuable natural landscapes, protected areas, cultural heritage, and other resources suitable for rural, nature-based, and sustainable tourism development. Previous research concerning transitional and rural economies has emphasized the importance of integrating environmental management, economic diversification, and market-oriented development strategies in strengthening regional development capacities (Cvijanović et al., 2013).

Despite the extensive international literature addressing environmental change and migration on the one hand, and sustainable tourism and rural development on the other, these relationships are frequently examined separately. Research on environmentally induced migration primarily focuses on the relationship between environmental stressors, vulnerability, adaptation, and population mobility (Black et al., 2011; McLeman, 2018), whereas sustainable tourism research predominantly examines destination management, environmental protection, economic benefits, and community participation (Hall, 2019; UNWTO, 2018). Considerably less attention has been devoted to empirically examining how local populations perceive the interconnected relationship between environmental degradation, migration processes, demographic change, and sustainable tourism development within a single analytical framework, particularly in the context of rural Serbia.

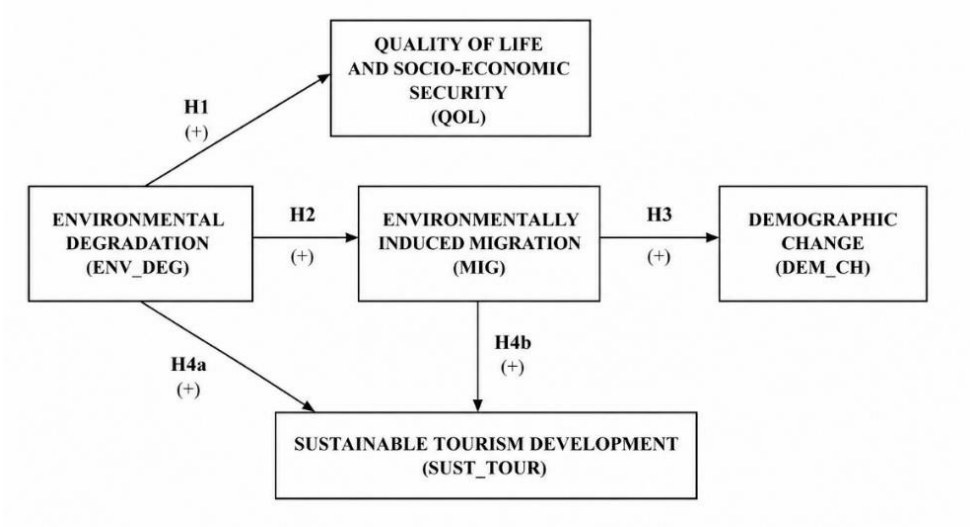
The study therefore adopts an integrated perspective in which environmental pressures may affect quality of life and migration tendencies, while migration processes may alter the demographic and economic capacity of local communities and subsequently influence opportunities for sustainable tourism development. Local residents' perceptions provide insight into how these interconnected changes are experienced and evaluated at the community level.

Accordingly, the aim of this study is to examine the perceived relationships between environmental degradation, environmentally induced migration, demographic and socioeconomic conditions, and sustainable tourism development in selected rural regions of the Republic of Serbia. More specifically, the study investigates whether perceived environmental degradation is associated with deterioration in quality of life and migration tendencies, whether environmentally induced migration is associated with demographic changes, and whether migration processes are related to the perceived sustainability of tourism development.

The novelty of the study lies in integrating environmental, demographic, and tourismdevelopment dimensions within a single empirical framework focused on rural Serbia. This approach contributes to understanding how environmental and demographic pressures may jointly shape local development opportunities and provides a basis for more integrated rural development policies.

Based on the theoretical framework and formulated hypotheses, Figure 1 presents the proposed relationships among environmental degradation, environmentally induced migration, quality of life and socio-economic security, demographic change, and sustainable tourism development.

Figure 1. Conceptual framework of the relationship between environmental degradation, environmentally induced migration, demographic change, quality of life, and sustainable tourism development



Source: Authors' conceptualization based on the research hypotheses.

Materials and methods

The empirical research was conducted among residents of selected environmentally vulnerable rural areas of the Republic of Serbia characterized by environmental pressures, demographic decline, and limited economic diversification, while simultaneously possessing natural and cultural resources relevant for tourism development. The study covered villages and settlements surrounding Potpeć Lake, Kamena Gora and Jabuka, as well as rural and riparian areas within the municipalities of Prijepolje and Priboj. In Eastern Serbia, respondents were drawn from the villages of Krivelj, Slatina, Oštrelj, Metovnica and Bučje in the surroundings of Bor, as well as rural settlements surrounding Majdanpek. The research also included peripheral villages in the Zlatibor area, including Sirogojno, Gostilje and Ljubiš, and villages surrounding Vlasina Lake in the municipality of Surdulica.

The study employed a non-probability sampling approach. The questionnaire was primarily distributed online to residents of the selected rural areas, while part of the data collection in the Zlatibor area was additionally conducted through direct field administration. The combined approach facilitated access to respondents from geographically dispersed rural communities while enabling direct participation in selected settlements. Participation was voluntary and anonymous, and respondents were informed about the purpose of the research and the use of the collected data prior to completing the questionnaire. The final sample consisted of 212 respondents of different gender, age groups and educational levels. The socio-demographic heterogeneity of

the sample enabled the examination of perceptions across different groups; however, the non-probability sampling procedure should be considered when interpreting and generalizing the findings beyond the surveyed population.

The research instrument consisted of 20 statements measuring respondents' perceptions of environmental degradation, environmentally induced migration, demographic change, quality of life and socio-economic security, and sustainable tourism development. All items were measured using a Likert-type scale. The complete questionnaire items and their theoretical foundations are presented in Table 1.

Table 1. Questionnaire items, thematic dimensions, and theoretical foundations

Item	Questionnaire statement	Thematic dimension	Supporting literature
Q1	Environmental degradation in my local area has increased in the past 5 years.	Environmental degradation	IPCC, 2022; FAO, 2018
Q2	The increase in environmental degradation affects tourism negatively in my region.	Environmental degradation / tourism	Gössling et al., 2015; Hall, 2019
Q3	I have considered migrating due to worsening environmental conditions.	Environmentally induced migration	Black et al., 2011; McLeman, 2018
Q4	Tourism development in my area has contributed to environmental degradation.	Environmental degradation / tourism impacts	Hall, 2019; UNWTO, 2018
Q5	Sustainable tourism practices are adequately implemented in my community	Sustainable tourism development	Hall, 2019; UNWTO, 2018
Q6	Population migrations are influenced by environmental changes in Serbia.	Environmentally induced migration	Black et al., 2011; Hugo, 2014
Q7	The government effectively manages environmental impacts related to tourism.	Sustainable tourism governance	UNWTO, 2018; Hall, 2019
Q8	Job opportunities in tourism influence population movements in my region.	Migration / tourism development	Hall & Williams, 2019
Q9	Environmental degradation has reduced the quality of life in my area.	Environmental degradation / quality of life	IPCC, 2022; FAO, 2018
Q10	Local communities support measures for sustainable tourism development.	Sustainable tourism / community participation	UNWTO, 2018; Hall, 2019
Q11	Migration decisions consider both economic and environmental factors.	Environmentally induced migration	Black et al., 2011; McLeman, 2018
Q12	Awareness about environmental issues and migration is widespread in my community.	Environmental awareness / migration	McLeman, 2018
Q13	Tourism industry stakeholders prioritize sustainability in their practices.	Sustainable tourism development	UNWTO, 2018; Hall, 2019
Q14	I feel tourism brings more benefits than harm to the environment locally.	Tourism impacts / sustainability	Hall, 2019
Q15	Environmental degradation causes more out-migration than other social factors.	Environmentally induced migration	Black et al., 2011; Hugo, 2014

Item	Questionnaire statement	Thematic dimension	Supporting literature
Q16	Public infrastructure supports sustainable development and environmental protection.	Sustainable development	Sachs, 2015; UNWTO, 2018
Q17	Tourism has created new economic opportunities for residents concerned about migration.	Tourism / local economic development	Hall & Williams, 2019
Q18	Population movements due to environmental reasons affect local demographics.	Demographic change	Castles, 2010; Black et al., 2011
Q19	Environmental education programs influence attitudes towards migration and tourism.	Environmental awareness	IPCC, 2022; UNWTO, 2018
Q20	There is sufficient cooperation between tourism and environmental sectors in Serbia.	Sustainable tourism governance	UNWTO, 2018; Hall, 2019

Source: Authors' elaboration based on the literature cited in the table

The questionnaire items were developed specifically for the purposes of the present study, drawing on theoretical and empirical literature concerning environmental degradation, environmentally induced migration, demographic change, quality of life, and sustainable tourism development. The cited sources in Table 1 therefore represent the theoretical foundations supporting the conceptualization of individual items rather than previously validated scales from which the statements were directly adopted. The 20 items address interconnected dimensions of environmental degradation, environmentally induced migration, demographic change, quality of life and socioeconomic conditions, and sustainable tourism development. Certain items intentionally address the intersections between these dimensions, reflecting the integrative conceptual framework of the study.

For hypothesis testing, selected questionnaire items were grouped into composite variables corresponding to the theoretical constructs examined in the study. The operationalization of the principal research constructs used for hypothesis testing is presented in Table 2.

Table 2. Operationalization of the research constructs

Research construct	Operational meaning
Environmental degradation (ENV_DEG)	Perceived deterioration of environmental conditions and natural resources and its consequences for local communities
Quality of life and socioeconomic security	Perceived effects of environmental pressures on quality of life and socioeconomic conditions
Environmentally induced migration (MIG)	Perceptions of environmental factors as drivers of migration

Research construct	Operational meaning
Demographic change	Perceived demographic consequences associated with environmentally induced migration
Sustainable tourism development (SUST_TOUR)	Perceptions of environmental and demographic influences on tourism sustainability

Source: Authors' elaboration based on the research questionnaire.

Composite indicators were constructed from conceptually related questionnaire items and subsequently used in the statistical analyses. The complete wording and theoretical basis of all 20 questionnaire items are presented in Table 1.

The internal consistency of the research instrument was assessed using Cronbach's alpha. Reliability analysis showed exceptionally high internal consistency for the complete 20-item questionnaire ($\alpha = 0.991$) and for the reduced 10-item set used in hypothesis testing ($\alpha = 0.981$). These values indicate a high degree of consistency among the questionnaire items and support their use in subsequent statistical analyses.

To examine the underlying dimensional structure of the questionnaire and obtain evidence regarding construct validity, an exploratory factor analysis (EFA) was performed using principal axis factoring (PAF). Sampling adequacy was evaluated using the Kaiser–Meyer–Olkin (KMO) measure, while Bartlett's test of sphericity was used to determine whether the correlation matrix was suitable for factor analysis. Factor retention was initially evaluated using eigenvalues greater than 1 and inspection of the scree plot. Given the theoretical expectation that the examined dimensions may be interrelated, an additional theoretically specified five-factor solution was examined using Promax oblique rotation. This procedure enabled comparison between the empirically derived factor structure and the five conceptually defined dimensions used in the study.

Statistical analysis was performed using SPSS. Descriptive statistics were used to summarize sample characteristics and response distributions. Pearson's correlation coefficient was applied to examine relationships between the main constructs, while Spearman's rank correlation coefficient was additionally calculated as a robustness check given the ordinal origin of the Likert-scale data (Field, 2018). Multiple linear regression was subsequently employed to examine the joint association of environmental degradation (ENV_DEG) and environmentally induced migration (MIG) with sustainable tourism development (SUST_TOUR). Statistical significance was evaluated at conventional significance levels.

As the study is based on respondents' perceptions and a cross-sectional design, the identified relationships represent perceived associations and should not be interpreted as direct causal effects.

Results

Socio-demographic profile of respondents

The socio-demographic characteristics of the sample are presented in Table 3. The sample was predominantly male (64.6%), while the largest age groups were 26–35 (34.4%) and 36–45 years (34.0%). Regarding education, most respondents had completed secondary (42.0%) or higher education (35.8%).

Table 3 Socio-demographic characteristics of respondents

Characteristics	Category	Frequency	Percentage (%)
Gender	Male	137	64.6
	Female	75	35.4
	Total	**212**	**100.0**
Age (years)	18–25	22	10.4
	26–35	73	34.4
	36–45	72	34.0
	46–55	43	20.3
	56–65	2	0.9
	Total	**212**	**100.0**
Education level	Primary education	6	2.8
	Secondary education	89	42.0
	Higher education	76	35.8
	Master's degree	36	17.0
	Doctoral degree	5	2.4
	Total	**212**	**100.0**

Source: Authors' calculations

Descriptive analysis of key research constructs

Descriptive statistics for the principal composite variables are presented in Table 4.

Mean scores were 1.99 (SD = 0.88) for environmental degradation (ENV_DEG), 2.41 (SD = 1.07) for environmentally induced migration (MIG), and 1.81 (SD = 0.71) for sustainable tourism development (SUST_TOUR). Among the three constructs, MIG showed the highest mean score and the greatest variability in respondents' perceptions.

Table 4. Descriptive statistics of composite variables

Variable	N	Minimum	Maximum	Mean	Std. Deviation
Environmental degradation (ENV_DEG)	212	1.00	5.00	1.99	0.88
Environmentally induced migration (MIG)	212	1.00	5.00	2.41	1.07
Sustainable tourism development (SUST_TOUR)	212	1.00	4.50	1.81	0.71

Source: Authors' calculations

Reliability and consistency of measurement

Reliability analysis indicated exceptionally high internal consistency for both the complete 20-item questionnaire (α = 0.991) and the reduced 10-item set used for hypothesis testing (α = 0.981) (Table 5). Given the magnitude of these coefficients, possible conceptual overlap among the measured dimensions was further examined through exploratory factor analysis.

Table 5. Reliability and consistency of measurement

Scale	Number of items	Cronbach's alpha
Full scale	20	0.991
Reduced scale (hypotheses testing)	10	0.981

Source: Authors' calculations

Exploratory Factor Analysis and Construct Structure

Exploratory factor analysis was conducted to examine the dimensional structure of the

20-item questionnaire. The data were highly suitable for factor analysis, with a Kaiser–Meyer–Olkin value of 0.952 and a statistically significant Bartlett's test of sphericity ($p < 0.001$). Principal axis factoring initially identified one dominant factor with an eigenvalue of 17.710, explaining 88.552% of the total variance. Factor loadings were uniformly high, ranging from 0.868 to 0.966, indicating a strong common underlying dimension across the questionnaire items (Table 6).

Table 6 Exploratory factor analysis of the 20-item questionnaire*****

Item	Factor loading	Communality
Q1	0.960	0.921
Q2	0.951	0.905
Q3	0.942	0.887
Q4	0.908	0.824
Q5	0.928	0.861
Q6	0.966	0.932
Q7	0.953	0.909
Q8	0.933	0.870
Q9	0.919	0.844
Q10	0.868	0.754
Q11	0.940	0.884
Q12	0.924	0.854
Q13	0.928	0.861
Q14	0.963	0.928
Q15	0.959	0.919
Q16	0.954	0.910
Q17	0.927	0.859
Q18	0.964	0.929
Q19	0.945	0.894
Q20	0.922	0.850

* KMO = 0.952; Bartlett's test: $\chi^2(190) = 10{,}168.288$, $p < 0.001$; eigenvalue of the first factor = 17.710; variance explained = 88.552%. Extraction method: Principal Axis Factoring.
Source: Authors' calculations

Given the theoretically defined multidimensional structure of the study, a five-factor solution was additionally examined using Promax oblique rotation. Although the rotated solution provided some differentiation among the theoretically proposed dimensions, substantial cross-loadings and strong factor interrelationships remained. Together with the exceptionally high Cronbach's alpha coefficients, these findings suggest considerable empirical overlap among the constructs and indicate that respondents may perceive environmental degradation, environmentally induced migration, demographic change, quality of life, and sustainable tourism development as interconnected dimensions of a broader rural vulnerability framework. The factor structure should therefore be interpreted with caution rather than as evidence of fully distinct latent constructs.

Testing hypothesis H1

Hypothesis H1 proposed that higher perceived environmental degradation is associated with lower perceived quality of life and greater socio-economic insecurity. Pearson's correlation showed an exceptionally strong and statistically significant association between the constructs ($r = 0.953$, $p < 0.001$), while Spearman's coefficient confirmed a similarly strong relationship ($\rho = 0.962$, $p < 0.001$) (Table 7). The consistency of the two coefficients indicates a robust association between perceived environmental degradation and adverse perceptions of living conditions and socio-economic security. Therefore, H1 was supported.

Table 7. Relationship between environmental degradation and quality of life (H1)

Variables	Pearson r	Spearman ρ	Significance (p)
ENV_DEG – Quality of life / security	0.953	0.962	< 0.001

Source: Authors' calculations

Testing hypothesis H2

Hypothesis H2 proposed that higher perceived environmental degradation is associated with stronger perceptions of environmentally induced migration. The results revealed an exceptionally strong and statistically significant association between ENV_DEG and MIG (Pearson $r = 0.953$, $p < 0.001$; Spearman $\rho = 0.962$, $p < 0.001$) (Table 8). Thus, respondents who perceived environmental degradation as more severe also tended to perceive stronger environmentally induced migration pressures. The consistency of the Pearson and Spearman coefficients supports the robustness of this relationship, and H2 was therefore supported. It should be noted that the coefficients reported for H2 differ slightly from those presented later within the general hypothesis (H0), as the hypothesis-specific analysis was based on the composite indicators constructed from the selected questionnaire items corresponding specifically to H2, whereas H0 was assessed using the broader composite constructs employed in the general conceptual model.

Table 8. Relationship between environmental degradation and environmentally induced migration (H2)

Variables	Pearson r	Spearman ρ	Significance (p)
ENV_DEG – MIG	0.953	0.962	< 0.001

Source: Authors' calculations

Testing hypothesis H3

Hypothesis H3 proposed that stronger perceptions of environmentally induced migration are associated with stronger perceptions of negative demographic change in rural communities. The relationship was exceptionally strong and statistically significant according to both Pearson's ($r = 0.974$, $p < 0.001$) and Spearman's ($\rho = 0.970$, $p < 0.001$) coefficients (Table 9). These findings indicate that stronger perceived migration pressures are closely associated with perceptions of population decline, ageing, and weakening demographic capacity in the surveyed rural communities.

Therefore, H3 was supported.

Table 9. Relationship between environmentally induced migration and demographic changes (H3)

Variables	Pearson r	Spearman ρ	Significance (p)
MIG – Demographic change	0.974	0.970	< 0.001

Source: Authors' calculations

Testing hypothesis H4

Hypothesis H4 proposed that environmental degradation and environmentally induced migration are associated with stronger perceptions of negative impacts on tourism development and its long-term sustainability. The correlation analysis showed a strong and statistically significant association between MIG and SUST_TOUR (Pearson $r = 0.866$, $p < 0.001$; Spearman $\rho = 0.917$, $p < 0.001$) (Table 10). This finding indicates that stronger perceived migration pressures are closely associated with greater perceived constraints on sustainable tourism development. The migration-related component of H4 was therefore supported, while the joint contribution of environmental degradation and migration was subsequently examined through multiple regression analysis.

Table 10. Relationship between environmentally induced migration and tourism sustainability (H4)

Variables	Pearson r	Spearman ρ	Significance (p)
MIG – SUST_TOUR	0.866	0.917	< 0.001

Source: Authors' calculations

Testing the general hypothesis (H0)

The general hypothesis H0 proposed that perceived environmental degradation is positively associated with environmentally induced migration and with perceived negative impacts on sustainable tourism development. As shown in Table 11, all three relationships were exceptionally strong and statistically significant. Pearson's coefficients ranged from 0.946 to 0.963, while Spearman's coefficients ranged from 0.947 to 0.959 (all $p < 0.001$). Specifically, ENV_DEG was strongly associated with MIG ($r = 0.946$; $\rho = 0.959$) and SUST_TOUR ($r = 0.956$; $\rho = 0.947$), while MIG was strongly associated with SUST_TOUR ($r = 0.963$; $\rho = 0.958$). These findings support H0 and indicate that respondents perceive environmental degradation, environmentally induced migration, and sustainable tourism development as closely interconnected dimensions of rural development.

Table 11. Correlations among environmental degradation, migration, and sustainable tourism development (H0)

Variables	Pearson r	Spearman ρ	Significance (p)
ENV_DEG – MIG	0.946	0.959	< 0.001
ENV_DEG – SUST_TOUR	0.956	0.947	< 0.001
MIG – SUST_TOUR	0.963	0.958	< 0.001

Source: Authors' calculations

Multiple Regression Analysis of the Proposed Conceptual Model

To complement the correlation-based hypothesis testing, multiple linear regression analysis was performed to examine the joint association of perceived environmental degradation (ENV_DEG) and environmentally induced migration (MIG) with sustainable tourism development (SUST_TOUR). SUST_TOUR was specified as the dependent variable, while ENV_DEG and MIG were entered simultaneously as predictors.

Table 12. Model Summary for the Multiple Regression Analysis*

Model	R	R^2	Adjusted R^2	Std. Error of the Estimate
1	0.973	0.946	0.946	0.16510

**Predictors: (Constant), MIG, ENV_DEG.*

Source: Authors' calculations

The model showed a very strong overall relationship ($R = 0.973$) and explained 94.6% of the variance in SUST_TOUR ($R^2 = 0.946$; adjusted $R^2 = 0.946$).

Table 13. ANOVA for the Multiple Regression Model*

Model	Sum of Squares	Df	Mean Square	F	p
Regression	100.714	2	50.357	1847.363	<0.001
Residual	5.697	209	0.027		
Total	106.411	211			

*Dependent variable: SUST_TOUR. Predictors: (Constant), MIG, ENV_DEG.
Source: Authors' calculations

The regression model was statistically significant, $F(2, 209) = 1847.363$, $p < 0.001$, indicating that ENV_DEG and MIG jointly provided significant prediction of SUST_TOUR.

Table 14. Regression Coefficients Predicting SUST_TOUR*

Predictor	B	Std. Error	β	t	p	Tolerance	VIF
Constant	0.227	0.028	-	7.992	<0.001	-	-
ENV_DEG	0.343	0.040	0.425	8.599	<0.001	0.105	9.525
MIG	0.371	0.033	0.561	11.362	<0.001	0.105	9.525

*Dependent variable: SUST_TOUR.

Source: Authors' calculations

Both ENV_DEG ($B = 0.343$, $\beta = 0.425$, $p < 0.001$) and MIG ($B = 0.371$, $\beta = 0.561$, $p < 0.001$) were statistically significant predictors of SUST_TOUR, with MIG showing the larger standardized coefficient. However, tolerance values of 0.105 and VIF values of 9.525 indicate substantial multicollinearity between the predictors. Together with the EFA findings and exceptionally high internal consistency, this suggests considerable empirical overlap between ENV_DEG and MIG. The individual regression coefficients should therefore be interpreted cautiously, with the model primarily demonstrating their strong joint association with sustainable tourism development rather than independent causal effects.

Table 15. Collinearity Diagnostics for the Regression Model*

Dimension	Eigenvalue	Condition Index	Constant	ENV_DEG	MIG
1	2.881	1.000	0.02	0.00	0.00
2	0.111	5.105	0.98	0.02	0.03
3	0.009	18.067	0.00	0.97	0.97

**Dependent variable: SUST_TOUR.*

Source: Authors' calculations

Collinearity diagnostics revealed a highest condition index of 18.067, which, together with the VIF values of 9.525, indicates substantial overlap between the predictors and warrants cautious interpretation of their individual regression coefficients.

Discussion

The results of this study provide strong empirical evidence that environmental degradation, environmentally induced migration, demographic change, and sustainable tourism development are perceived as closely interconnected processes in the selected rural regions of Serbia. The exceptionally strong relationships identified between the analyzed constructs suggest that local residents do not perceive environmental, demographic, and economic challenges as isolated phenomena, but rather as mutually reinforcing dimensions of a broader rural development problem. This interpretation is particularly relevant in environmentally vulnerable rural areas, where ecological pressures coexist with population decline, ageing, limited employment opportunities, and restricted economic diversification.

One of the key findings concerns the relationship between perceived environmental degradation and quality of life and socio-economic security. The strong association between these dimensions indicates that respondents relate deteriorating environmental conditions to broader concerns regarding living standards, livelihood security, and future economic opportunities. This finding is consistent with the sustainable livelihoods perspective, according to which environmental resources constitute an important component of the asset base upon which rural households depend (Scoones, 2015). In rural areas where agriculture, natural resources, and place-based economic activities remain important, environmental deterioration may therefore have consequences extending beyond ecosystem quality to household income and employment opportunities. In this sense, the present findings support the broader argument that environmental degradation should not be treated exclusively as an ecological issue, but as a development constraint affecting multiple dimensions of rural well-being.

The strong relationship between environmental degradation and environmentally induced migration further supports the growing body of literature that treats environmental change as one component of a multi-causal migration process. Previous studies have emphasized that environmental pressures rarely operate as independent determinants of migration; rather, they interact with economic conditions, employment opportunities, household resources, institutional settings, and existing social vulnerabilities (Black et al., 2011; McLeman, 2018). This interpretation is consistent with Castles (2002), who cautioned against environmentally deterministic explanations of migration, and Foresight (2011), which conceptualized environmental change as interacting with economic, social, political, and demographic drivers of mobility. From a broader migration-theory perspective, migration decisions depend not only on external pressures but also on the aspirations, resources, and capabilities of individuals and households (de Haas, 2010, 2021).

At the same time, the results should not be interpreted as evidence that environmental degradation directly causes migration. The cross-sectional and perception-based design does not allow causal inference, and migration decisions remain inherently multidimensional. Rather, the findings indicate that residents perceive environmental deterioration as closely connected with conditions that may encourage population mobility. This distinction is particularly important in Serbia, where rural migration and depopulation predate many contemporary environmental concerns and are also shaped by long-term economic restructuring, regional inequalities, employment opportunities, and population ageing. Previous research has identified structural and profitability constraints within Serbian rural and agri-food sectors that may further limit local development capacity and interact with environmental and demographic pressures (Domanović et al., 2018). Environmental degradation should therefore be interpreted as an additional and potentially reinforcing pressure rather than as a single explanation for rural out-migration.

The relationship between environmentally induced migration and negative demographic change represents another important dimension of the findings. Respondents strongly

associated migration with population ageing, labour shortages, and declining local development capacity. This pattern corresponds with broader research on rural depopulation showing that persistent out-migration, particularly among younger and economically active populations, can accelerate demographic ageing and weaken the human-capital base of rural communities (Johnson & Lichter, 2019). A declining working-age population can also reduce entrepreneurial activity, weaken local markets and services, and diminish the capacity of communities to initiate new development activities. Migration can therefore be understood not only as an outcome of unfavourable local conditions, but also as a mechanism through which existing environmental and socio-economic vulnerabilities may be reproduced over time. This interpretation is consistent with migration theories emphasizing that migration can reshape areas of origin through selective population loss and changes in the composition of the remaining population (Massey et al., 1993; King, 2012), affecting labour availability, human capital, social networks, and the long-term economic capacity of rural communities.

These demographic effects are particularly important when considering sustainable tourism development. The results indicate strong associations between environmental degradation, environmentally induced migration, and perceived constraints on tourism sustainability. This finding is consistent with the broader sustainable tourism literature, which emphasizes that tourism development depends not only on attractive natural resources but also on their long-term preservation and effective management (Hall, 2019; UNWTO, 2018). Environmental degradation may reduce landscape quality, ecosystem services, and the overall attractiveness of rural destinations, thereby weakening the natural-resource base on which many forms of rural and nature-based tourism depend.

However, the results also point to a second mechanism that is sometimes less explicitly considered: tourism sustainability depends on demographic capacity as well as environmental quality. Continued migration can reduce the availability of local labour, potential entrepreneurs, service providers, and community members capable of participating in destination development. It may also weaken the preservation of local traditions, knowledge, and cultural practices that contribute to the authenticity of rural tourism. This interpretation corresponds with studies emphasizing the role of local communities, human resources, and participation in successful rural and sustainable tourism development (Rosalina et al., 2021; López-Sanz et al., 2021). From this perspective, environmental degradation and migration may affect tourism through different but mutually reinforcing pathways.

The relationship is nevertheless not necessarily unidirectional. Sustainable tourism can itself represent a potential mechanism for rural economic diversification and local revitalization. Previous research has shown that appropriately planned rural tourism may generate employment, support small businesses, valorize local products and cultural resources, and create supplementary sources of household income (Rosalina et al., 2021; López-Sanz et al., 2021). These effects may be particularly relevant in depopulating areas with limited alternative economic opportunities. The findings

therefore suggest a potentially important development dynamic: environmental degradation and migration may constrain tourism development, while well-managed sustainable tourism may contribute to improving local economic opportunities and reducing some socio-economic pressures associated with out-migration. Such benefits, however, should not be assumed automatically, since poorly managed tourism may itself generate environmental pressures and undermine the resources on which destination competitiveness depends (Hall, 2019).

Although sustainable tourism may provide opportunities for economic diversification, its capacity to reverse rural decline should not be overstated. Tourism development can generate employment and supplementary income, but its benefits depend on effective planning, local participation, appropriate governance, and the protection of the environmental resources on which tourism relies (Weaver, 2006; Hall & Lew, 2009). This supports the view of sustainable tourism as an adaptive and context-dependent development approach rather than a universally applicable solution (Hunter, 1997; Saarinen, 2006).

An important aspect of the results concerns the exceptionally strong statistical relationships among the analyzed constructs. The high internal consistency of the questionnaire, the dominant general factor identified by exploratory factor analysis, and the high correlations and regression coefficients collectively indicate considerable empirical overlap among perceptions of environmental degradation, environmentally induced migration, demographic change, and tourism-related consequences. The substantial multicollinearity observed between ENV_DEG and MIG further supports the need for cautious interpretation of their individual effects. These findings suggest that respondents may perceive the analyzed issues as components of a broader underlying dimension of rural environmental and socio-economic vulnerability rather than as entirely separate processes.

This overlap is theoretically meaningful because environmental, demographic, and economic pressures frequently occur simultaneously in vulnerable rural areas. Nevertheless, it also requires methodological caution. The very high correlations should not be interpreted as evidence that the constructs are identical or that one necessarily causes another. Instead, they may partly reflect the interconnected nature of the phenomena, the perceptual character of the measurement instrument, and similarities in respondents' evaluations of related statements. Future studies should therefore examine the discriminant validity of these dimensions using larger and more diverse samples and, where appropriate, confirmatory factor analysis or structural equation modeling. Combining perceptual measures with objective environmental, demographic, and tourism indicators would enable a more rigorous examination of these relationships.

The multiple regression analysis provides additional support for the proposed conceptual framework beyond the bivariate correlations. ENV_DEG and MIG jointly explained a very high proportion of variance in SUST_TOUR ($R^2 = 0.946$), while both predictors were statistically significant. However, the substantial multicollinearity between the

predictors (VIF = 9.525) requires cautious interpretation of their individual coefficients. Rather than demonstrating independent causal effects, the regression results indicate that environmental degradation and environmentally induced migration are closely related and jointly associated with sustainable tourism outcomes.

Taken together, the findings support an integrated interpretation of rural development in which environmental quality, population dynamics, and tourism development are interconnected. This perspective challenges sectoral approaches that address environmental protection, demographic decline, or tourism development independently. In environmentally vulnerable rural regions of Serbia, tourism policies may have limited long-term effectiveness if environmental degradation continues or demographic decline reduces the human resources necessary for local development. Conversely, environmental protection measures may generate broader development benefits when combined with initiatives supporting employment, local entrepreneurship, community participation, and sustainable tourism.

The findings therefore point to the need for place-sensitive and integrated rural development strategies. Such strategies should combine environmental rehabilitation and resource protection with measures aimed at strengthening local economic opportunities, supporting younger and economically active residents, encouraging entrepreneurship, and developing tourism based on the sustainable use of natural and cultural resources. Sustainable tourism should therefore not be viewed as an isolated solution to rural depopulation, but as one component of a broader development framework linking environmental protection, economic diversification, and community resilience.

Conclusions

The findings of this study demonstrate that environmental degradation, environmentally induced migration, demographic change, and sustainable tourism development are strongly interconnected in the selected rural regions of Serbia. Based on the perceptions of local residents, environmental pressures are closely associated with reduced quality of life and socio-economic security and with stronger perceptions of environmentally induced migration. Migration, in turn, is associated with negative demographic changes and perceived constraints on the long-term sustainability of tourism development. These findings support an integrated understanding of rural vulnerability in which environmental, demographic, and economic processes should not be considered in isolation.

From a theoretical perspective, the study contributes to the literature by integrating environmental degradation, environmentally induced migration, demographic change, quality of life, and sustainable tourism within a common analytical framework. While previous research has frequently examined these processes separately, the present study demonstrates how local residents perceive them as closely interconnected dimensions of rural development. In particular, the findings extend the discussion of environmentally induced migration by highlighting its perceived relationship not only with environmental and socio-economic pressures, but also with demographic capacity

and the conditions necessary for sustainable tourism development. This integrated perspective represents the principal theoretical contribution of the study.

The findings also have important policy implications. Environmental protection should be treated as an integral component of rural development policy rather than as a separate environmental agenda. Measures aimed at improving environmental quality and protecting natural resources may simultaneously strengthen the conditions for rural livelihoods and tourism development. Likewise, policies addressing migration and demographic decline should be coordinated with local economic development strategies supporting employment, entrepreneurship, infrastructure, and economic diversification in vulnerable rural communities.

Sustainable tourism may represent an important component of such diversification, particularly in regions with valuable natural and cultural resources, but should not be regarded as an automatic solution to rural depopulation. Its long-term contribution depends on environmental quality, local participation, appropriate infrastructure, and effective destination management. Sustainable tourism policies should therefore be integrated with broader environmental, demographic, and regional development strategies.

Several limitations should be acknowledged. The study is based on respondents' perceptions and a cross-sectional research design; consequently, the identified relationships should not be interpreted as direct causal effects. The exceptionally strong correlations and the substantial overlap identified through exploratory factor and regression analyses indicate that respondents may perceive these processes as dimensions of a broader rural vulnerability. Future studies should examine these relationships using larger and more geographically diverse samples, objective environmental and demographic indicators, longitudinal and spatial data, and confirmatory approaches such as CFA or structural equation modeling.

Overall, the study provides empirical support for approaching environmentally vulnerable rural regions as integrated socio-environmental systems in which environmental quality, population dynamics, and economic development interact. By connecting environmentally induced migration with demographic change and sustainable tourism development, the research contributes to further theoretical development and provides a framework for more integrated rural development policies in Serbia.

Conflict of interests

The authors declare no conflict of interest.

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STRUCTURAL CHANGES AND PERFORMANCE OF SERBIAN AGRICULTURE AFTER 2000

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ABSTRACT

Agricultural policy in Serbia during the transition period has failed to bring the agricultural sector closer to the development level of advanced European Union economies. The sector has been characterized by short-term measures, lack of strategic planning, outdated technologies, and low capitalization, resulting in limited value added and low productivity. This research examines the structural changes and development of agriculture in Serbia during the transition period, with emphasis on production structure and agricultural policy directions. The results indicate that crop production still dominates total agricultural output, while livestock production remains underdeveloped compared to developed economies, indicating a low level of processing and sustainable intensification. The analysis also shows that developed countries increasingly support environmentally sustainable small and medium-sized farms. Although Serbia's agricultural budget has recently exceeded 6% of the national budget, the achieved results remain significantly below the country's objective potential and comparative advantages.

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Introduction

The primary objective of agricultural development in Serbia is to transform the sector in order to achieve compatibility with the agricultural systems of the European Union. Certain progress has been made in terms of production structure and specialization; however, a substantial gap relative to developed countries persists, particularly from the perspective of productivity (Aničić et al., 2021). Significant differences compared to EU agriculture are also reflected in ownership structures, farm sizes, land use patterns, as well as in financing mechanisms and access to credit. The structure of agricultural production in Serbia is dominated by crop production, accounting for approximately two-thirds, while livestock production represents only one-third—contrary to the structure observed in the most developed economies. The Common Agricultural Market offers considerable opportunities but also imposes numerous obligations, including regulatory harmonization and compliance with established standards. Increased exposure to competition necessitates modernization, restructuring of production, changes in farm size, and greater specialization. At the same time, the focus of agricultural support in the EU is shifting toward the promotion of small and medium-sized farms based on environmentally and socially sustainable technologies.

Serbian agriculture continues to be characterized by the widespread use of outdated technologies and insufficiently capitalized production with low value added, resulting in significantly lower productivity compared to developed countries. Enhancing productivity requires adequate investment and financing throughout the entire agri-food value chain (Trifunović et al., 2024). Due to slow capital turnover, low profitability, and the lack of internal financing sources, the agricultural sector in Serbia requires financial and credit support, which should be provided with strong state involvement. Innovation and adaptation to the increasingly demanding preferences of consumers represent essential determinants of competitiveness in international markets. For many years, Serbian agriculture has maintained a positive trade balance and a significant share in the country's overall foreign trade. However, it is necessary to eliminate the prevailing practice whereby rising agricultural product prices disproportionately benefit intermediaries, while producers receive the smallest share of gains. A positive signal for further development has been provided by the competent ministry through a significant increase in the agricultural budget, which reached RSD 125.7 billion in 2024, accounting for 6.74% of the national budget.

The aim of this paper is to highlight the importance of structural changes in the agricultural sector as a prerequisite for aligning Serbian agriculture with that of developed EU countries in terms of productivity, farm size, financing mechanisms, and various forms of support. In this way, the sector can respond more effectively to increasingly complex and diversified consumer demands. It is evident that existing comparative advantages have not been fully utilized, suggesting that there is substantial potential to enhance the competitiveness of the agricultural sector and achieve improved results in foreign trade.

Literature review

Structural Changes in the Agricultural Sector of Transition Economies and the European Union

The transformation of the agricultural sector in the Republic of Serbia has not yet been completed, with the most significant processes involving changes in ownership structure, farm size, and land use patterns. These changes are largely determined by the broader economic transition and the process of European Union accession (Lalić & Trifunović, 2026). In addition, new challenges have emerged, particularly those related to climate change, environmental degradation, and biodiversity loss. The most pronounced gap in the agricultural sector remains the lag in productivity compared to developed European countries. Structural changes in agriculture are also strongly influenced by unfavorable demographic trends, including rural depopulation, a decline in household size, and population aging.

The primary objective of agricultural development is to transform the sector in order to achieve compatibility with the agricultural systems of the European Union. Agricultural development primarily aims to transform the sector by aligning its institutional, economic, and production frameworks with those of the European Union.While some progress has been made in terms of production structure and specialization, a significant gap relative to developed countries persists, particularly in terms of productivity and sustainable intensification. Structural constraints such as inadequate infrastructure, weak institutional support, and limited entrepreneurial capacity continue to hinder sustainable growth (Bejatović & Ristić, 2016).

The transformation of agricultural systems in transition economies is largely shaped by economic transition and EU accession processes, especially through changes in ownership structures, farm size distribution, and land use patterns (Swinnen & Vranken, 2010). Agricultural production in most developing countries is significantly constrained by limited access to financial resources, as it often operates within a vicious cycle of low incomes, insufficient savings, and low levels of investment, which inevitably leads to dependence on state support (Aničić et al., 2023).

The Common Agricultural Market provides numerous benefits through the Common Agricultural Policy, facilitating and accelerating the flow of goods. At the same time, it imposes a wide range of obligations, including regulatory harmonization and compliance with relevant standards. The sector is exposed to strong competitive pressures, which necessitate modernization, restructuring of production, changes in farm size, and increased specialization (Czubak & Pawłowski, 2020). After more than three decades of transition, numerous studies confirm that the agricultural sector in transition economies continues to differ significantly from that of developed countries, particularly in terms of high fragmentation (Radlińska, 2024).

The agricultural sector is increasingly affected by climate change and environmental degradation, leading to more frequent occurrences of droughts, floods, and wildfires

(Stošić et al., 2024; Bučalina Matić et al., 2024). In response to these challenges, the European Green Deal was adopted in 2019 (EC, 2019), aiming to establish a competitive economy by 2050 with net-zero greenhouse gas emissions and economic growth decoupled from resource use (Arabadjueva & Bogojević, 2024). All countries are required to update their climate neutrality strategies every ten years, with agricultural sector development identified as a key priority. These strategies must also be aligned with the United Nations Sustainable Development Goals for 2030 (UN, 2015).

The development of the agricultural sector in the European Union is guided by the European Green Deal, the Farm to Fork Strategy, and the EU Biodiversity Strategy (EC, 2020). These three strategic documents constitute a comprehensive framework for the agricultural sector, within which policies and measures promote sustainable and environmentally friendly food production systems (Boix-Fayos & De Vente, 2023). The focus of support is increasingly shifting toward the promotion of small and medium-sized farms based on environmentally and socially sustainable technologies (Guth et al., 2020).

Agricultural holdings in transition economies differ from those in developed countries in terms of economic strength, agrarian structure, level of mechanization, employment, and specialization (Banski & Mazur, 2021). The agricultural sector in transition economies is characterized by a high share of small farms (up to 5 hectares) with limited economic capacity (Slamová & Belčáková, 2019). Agricultural policies in these countries have been primarily oriented toward the modernization of technology and infrastructure, as well as toward increasing productivity and innovation (Fan et al., 2024). Agricultural production in these economies also plays a crucial role in the preservation and restoration of biodiversity, although it requires specific forms of financial support (Rossi, 2022).

The transformation of agricultural holdings in transition economies has largely followed the models of Germany and France, where strength is based on large-scale farms characterized by high efficiency and economies of scale. The main objective has been to ensure food security for EU citizens at affordable prices (Ostojić, Petrović & Despotović, 2025). However, the objectives of the European Green Deal require that high productivity in large farms be achieved with minimal water waste and reduced use of fertilizers and plant protection products (Shin et al., 2022). In livestock production, the goal is to increase productivity while simultaneously reducing negative environmental impacts (Tryjanowski et al., 2011). By 2030, artificial intelligence is expected to enable more efficient allocation of resources and yields (LaFevor & Magliocca, 2021).

The European Green Deal also emphasizes that small farms can play a key role in the transformation of the agricultural sector. Their development is supported through EU regulations promoting organic agriculture and the achievement of competitive advantages (Panzaru et al., 2023). The concept of organic agriculture is based on economic, environmental, and social benefits. Its effects are reflected in the optimization of resource use, increased biodiversity, regional development, and

reduced environmental pollution. In the long term, it enhances the resilience of the agricultural sector to climate change (RZS, 2025). The transition toward a resilient organic production model also requires the introduction of appropriate financial support mechanisms for small organic farms.

Small farms are increasingly engaging in direct sales to consumers. The formation of cooperatives shortens supply chains, reduces transportation costs, and supports local agriculture. The use of pesticides is reduced, while pasture-based systems are increasingly favored over intensive livestock production. In both crop and livestock production, these practices reduce negative impacts on climate and the environment, while regenerative agricultural practices contribute to improving soil quality (Gascuel-Odoux et al., 2022; Panić et al., 2025; Lalić & Trifunović, 2026).

According to estimates by the European Bank for Reconstruction and Development (EBRD, 2024), transition economies in Central and South-Eastern Europe have achieved modest annual improvements in competitiveness. Compared to 2016, access to finance for small and medium-sized enterprises has improved, along with labor productivity and the quality of logistics services. During the period 2016–2024, the SEE region has improved its competitiveness through an increase in the number of new enterprises, enhanced logistics performance, higher labor productivity, and more sophisticated service exports. The most competitive economies are the Czech Republic, Slovakia, Poland, and Slovenia. Serbia has recorded the greatest progress in the areas of integration, inclusiveness, and the green economy during the same period (RZS, 2025).

A key question arises as to how productivity can be increased in the context of revised EU regulatory measures aimed at strengthening efficiency and sustainability. Agricultural productivity is influenced by three main groups of factors: producers, consumers, and agricultural markets. In addition, the social dimension of agriculture and global challenges related to population growth must be taken into account (Alexandratos & Bruinsma, 2012). Numerous studies examining the relationship between productivity and farm size indicate that larger production volumes do not necessarily imply farm enlargement, and that purchase prices may vary depending on farm size (Huan et al., 2022).

Farmers face numerous challenges, including extreme weather events, input shortages, high production costs, price volatility, and environmental regulations (Bizzo et al., 2023). Research on the resilience and adaptability of EU agriculture highlights the interaction of three major categories of challenges (Barreiro-Hurle et al., 2024; Vigani et al., 2024): the interplay between climate change and environmental sustainability, changing food consumption patterns, and the dynamics of globalization.

In order to reach its full potential, Serbian agriculture must overcome its overall low level of productivity. The sector remains characterized by the use of outdated technologies and insufficiently capitalized production with low value added. Therefore, improving productivity requires investment, adequate financing, and support across the entire agri-food value chain (Atanasijević & Danon, 2014). Knowledge, as a source of innovation and a driver of successful adaptation to increasingly demanding consumer

preferences, represents a key determinant of competitiveness in international markets (Vasiljević & Savić, 2014).

Serbian agriculture requires financial and credit support due to slow capital turnover, low profitability, and the lack of internal financing sources, which should be provided with strong state involvement. The need for a greater role of the state is also driven by underdeveloped financial markets and institutions (Radović, 2015).

Access to finance for farmers and the agri-food sector as a whole has been constrained for years due to numerous interrelated limitations influenced by legal, economic, and institutional factors (Dimitrijević, 2023). Regional specificities and the diversity of farm types have been inconsistently addressed by agricultural policy. Support schemes have lacked clearly defined objectives and implementation mechanisms, resulting in limited effectiveness (Bogdanov, 2014).

The literature reviewed suggests that agricultural transformation in transition economies is shaped by a complex interaction of structural, institutional, financial, environmental, and technological factors. While the European Union has increasingly oriented agricultural policy toward sustainability, innovation, and value-added production, many transition economies continue to face challenges related to fragmented farm structures, insufficient capitalization, and productivity gaps. In this context, Serbia represents a particularly relevant case, as it combines significant natural and export potential with persistent structural constraints. Therefore, examining the performance and structural evolution of Serbian agriculture provides an opportunity to assess the extent to which current development patterns are aligned with contemporary European agricultural trends and policy objectives.

Materials and Methods

This study is based on a descriptive, comparative and trend analysis of structural changes and development performance of the agricultural sector in the Republic of Serbia. The research combines quantitative analysis of secondary statistical data with a review of relevant scientific literature and policy documents related to agricultural development in transition economies and the European Union.

The empirical analysis relies on data obtained from the Statistical Office of the Republic of Serbia (SORS), the Ministry of Agriculture, Forestry and Water Management (Green Book reports), Eurostat, the European Bank for Reconstruction and Development (EBRD), and other relevant national and international institutions. The observed period covers primarily the years 2020–2024, while selected indicators and literature sources are used to provide a broader perspective on structural changes that have taken place since 2000. The applied research methodology includes descriptive statistical analysis, comparative analysis, trend analysis, and structural analysis of key indicators of agricultural development. Particular attention is devoted to gross value added, employment, foreign trade performance, production structure, agricultural budget support, and productivity-related indicators. Comparative analysis was used to assess the position of Serbian agriculture relative to selected transition economies and developed European Union member states.

The research is based on the assumption that the long-term competitiveness and sustainability of Serbian agriculture depend on structural transformation, productivity growth, improved capitalization, stronger livestock production, and more efficient agricultural policy measures.

Results and Discussions

Performance Outcomes and Foreign Trade

In the contemporary global environment, there is a clear trend of increasing demand and structural changes in the demand for agricultural products (Aničić et al., 2025). Such dynamics require a strong market orientation of agricultural producers, ranging from agribusiness enterprises to individual farms. Sustaining a competitive position in advanced global markets necessitates enhancing the competitiveness of the entire sector, based on the application of modern knowledge and innovation, as well as on the synergistic interaction of all competitiveness factors (Anufrijev et al., 2025).

The performance of Serbia's agricultural sector is shaped by a combination of external factors—such as globalization, liberalization, technological progress, climate change, limited availability of natural resources, and demographic changes—and internal factors, including the size of agricultural holdings, the structure of the sector, sources of productivity growth, the use of technology, and the level of knowledge and information (Aničić, et al.,2023). At the same time, the state and local governments play a crucial role in creating a supportive socio-economic environment for the development of rural areas and agriculture, particularly in less developed regions of the Republic of Serbia.

Data presented in Table 1 illustrate trends in the gross value added (GVA) of agriculture, employment, and foreign trade (exports and imports) over the period 2020–2024. In addition, data from the Statistical Office of the Republic of Serbia (SORS) provide a comparative perspective on the position of Serbian agriculture relative to neighboring countries and developed EU economies.

Table 1. Share of the Agricultural Sector in Key Macroeconomic Indicators, 2020–2024

Indicator	2020	2021	2022	2023	2024
GVA of the agricultural sector at current prices (million RSD)	291,305	339,051	398,174	333,893	303,410
Share in total GVA (%)	6	6.2	6.3	4.4	3.7
Number of employed persons (thousands)	421.4	390.5	390.7	373.2	371.9
Share in foreign trade – exports (%)	21.3	19	17.3	16.2	17.4
Share in foreign trade – imports (%)	8.9	8.4	8	9.1	9.7

Source: Statistical Office of the Republic of Serbia (SORS), 2025

According to the Statistical Office of the Republic of Serbia (2025, pp. 66–80) the average utilized agricultural area per holding in developed European countries amounted to 38 hectares in 2020, while in transition economies it was only 15 hectares—2.5 times lower. The process of land consolidation has been particularly slow in Romania (4.4 ha), Greece (5.3 ha), and Serbia (6.4 ha). In contrast, the largest average farm sizes are recorded in Denmark and France (approximately 70 ha each). In terms of productivity, the highest levels are observed in the Netherlands (EUR 157,000 per holding), while the lowest are recorded in Romania (EUR 10,000) and Serbia (EUR 12,000). According to Eurostat data, the average share of agricultural GVA in GDP over the last decade has ranged between 1.3% and 1.4%. In the group of the most developed countries, this share has been around 1%, while in transition economies it declined from an average of 2.8% of GDP in 2013 to 1.8% in 2023. In 2023, the highest shares of agricultural GVA in GDP were recorded in Serbia (4%), Romania (3.1%), and Greece (2.8%) (SORS, 2025).

The findings presented in Table 1 reveal a structural paradox of Serbian agriculture. Although the sector maintains a relatively high share in gross value added and foreign trade compared with many EU member states, these indicators do not necessarily reflect a high level of productivity or competitiveness. On the contrary, the relatively large contribution of agriculture to total GVA is partly a consequence of the lower level of overall economic development and the slower structural transformation of the economy. At the same time, the comparatively small average farm size and low productivity per holding indicate that Serbian agriculture continues to rely predominantly on extensive production patterns and primary agricultural commodities. These findings are consistent with previous studies highlighting the persistence of structural constraints in transition economies, particularly fragmented land ownership, insufficient capitalization, and limited technological modernization.

Compared with developed EU countries, where productivity growth has been largely driven by technological innovation, specialization, and economies of scale, Serbian agriculture continues to face significant challenges in improving efficiency and increasing value added. Therefore, future development should focus not only on expanding production volumes but also on strengthening processing capacities, innovation adoption, and integration into higher-value segments of the agri-food value chain.

The data presented in Table 1 provide additional insight into the macroeconomic position of agriculture and its role within the overall economy. Although the sector maintains a relatively significant share in foreign trade, particularly on the export side, its contribution to gross value added and employment shows a declining trend over the observed period. This indicates that, despite its strong external orientation, the sector faces structural limitations in generating higher value added and employment.

These trends are consistent with the previously observed structural characteristics of Serbian agriculture. The dominance of crop production, combined with the decline in

livestock production, contributes to lower value-added generation and weaker vertical integration within the agri-food value chain. Furthermore, the relatively small share of agriculture in total GVA, alongside modest employment participation, reflects the sector's limited productivity compared to developed EU economies.

At the same time, the positive foreign trade balance and the relatively high share of agricultural exports highlight the sector's comparative advantages, particularly in primary production. However, the data suggest that these advantages are not sufficiently transformed into higher levels of processing and value-added activities.

Overall, the evidence from Table 1 confirms that Serbian agriculture operates within a dual framework: on the one hand, it remains an important export-oriented sector, while on the other, it is constrained by structural inefficiencies that limit its contribution to broader economic development.

According to the **Statistical Office of the Republic of Serbia** (2025, pp. 66–80) in Sector A – Agriculture, Forestry and Fisheries, approximately 3,000 enterprises operated in 2023, employing around 24,000 workers and generating EUR 600 million in gross value added. The agricultural sector accounted for 1.5% of total gross value added in the economy and 1.8% of total employment. Regarding cooperatives, according to data from the Statistical Office of the Republic of Serbia (SORS) for 2023, out of a total of 2,117 registered cooperatives, only 1,502 were active. The cooperative sector faces numerous systemic challenges, including inadequate regulatory frameworks, limited working capital, unfavorable tax policies, and insufficient access to credit support. The structure of agricultural production in Serbia is dominated by crop production, which accounts for approximately two-thirds of total output, while livestock production represents one-third, an inverse structure compared to that of the most developed economies. Over the past decade, total agricultural production in Serbia has increased from EUR 5 billion to EUR 6.59 billion. However, this growth has been accompanied by a decline in livestock production and an expansion of crop production (SORS, 2025).

Table 2. Indices of Gross Agricultural Production in Serbia, 2020–2024 (previous year = 100)

Indicator	**2020**	**2021**	**2022**	**2023**	**2024**
Total agricultural production	102.9	92.5	91.7	108.5	92.4
Crop production	104.6	89.9	88.7	115.5	87.9
Livestock production	99.7	98.6	98.7	95.1	101.4

Source: Ministry of Agriculture, Forestry and Water Management (MAFWM), *Green Book*

The data presented in Table 2 indicate pronounced volatility in agricultural production in Serbia over the observed period. Total agricultural output fluctuates significantly, with a notable decline in 2021 and 2022, followed by a temporary recovery in 2023, and a renewed decrease in 2024. This variability is primarily driven by crop production, which exhibits strong cyclical movements and is highly sensitive to external factors such as weather conditions and input availability. In contrast, livestock production

shows relatively stable but modest dynamics, with a slight downward trend until 2023 and a mild recovery in 2024. Overall, the results suggest that Serbian agriculture remains structurally vulnerable, with a high dependence on crop production and limited stabilization capacity from the livestock sector, which further constrains the sector's long-term sustainability and resilience.

In 2024, the share of agricultural products in total exports increased from 16.2% in 2023 to 17.4%, while the share in total imports also rose from 9.1% in 2023 to 9.7% in 2024. Total trade in 2024 reached nearly EUR 9 billion, representing an increase of 11.4% compared to 2023. The total value of exports of agri-food products amounted to EUR 5.1 billion, while imports reached EUR 3.8 billion (MAFWM, 2025). The export structure continues to be dominated by primary agricultural commodities, such as maize, frozen raspberries, wheat, refined sunflower oil, and fresh apples. Of the total agricultural exports in 2024, 49.1% were directed toward the European Union, followed by CEFTA countries with a share of 28.3%.

Despite the consistently positive trade balance and growing export performance, the structure of Serbia's agricultural exports reveals a persistent reliance on primary commodities with relatively low value added. This indicates the existence of a "high export, low value-added" pattern, where comparative advantages are primarily realized in raw or minimally processed products.

Such a structure limits the potential for greater income generation, productivity growth, and stronger integration into higher segments of global value chains. Therefore, enhancing the level of processing and increasing the share of higher value-added products remain key challenges for improving the overall competitiveness and long-term sustainability of the agricultural sector.

Table 3. Key Indicators of Foreign Trade in Agri-Food Products, 2020–2024

Indicator	2020	2021	2022	2023	2024
Exports (million EUR)	3,635	4,163	4,765	4,637	5,091
Imports (million EUR)	2,048	2,442	3,138	3,345	3,804
Trade balance (million EUR)	1,587	1,721	1,627	1,292	1,287
Trade volume (million EUR)	5,683	6,605	7,903	7,982	8,895
Export coverage of imports (%)	177.5	170.5	151.8	138.6	133.9
Share in total trade of the Republic of Serbia (%)	14.2	9.9	11.9	12.2	13
Share of exports in total exports of the Republic of Serbia (%)	21.3	15.1	17.3	16.2	17.4
Share of imports in total imports of the Republic of Serbia (%)	8.9	6.3	8	9.1	9.7

Source: Ministry of Agriculture, Forestry and Water Management (MAFWM), *Green Book*

These findings are consistent with previous studies on agricultural development in transition economies, which emphasize that export growth based predominantly on primary commodities rarely leads to substantial productivity gains or sustained improvements

in competitiveness. Similar patterns have been identified in several Central and South-Eastern European countries, where positive trade balances coexist with relatively low levels of processing, technological intensity, and value-added generation.

The empirical findings indicate that Serbian agriculture maintains a relatively strong position in foreign trade, reflected in a persistent trade surplus and a growing share in total exports. However, this performance is largely driven by primary agricultural commodities with low value added, pointing to structural limitations in the sector's development model.

At the same time, key structural indicators, such as low productivity, fragmented farm structure, insufficient capitalization, and limited access to finance, highlight a significant gap compared to developed EU economies. The volatility of production, particularly in crop agriculture, further underscores the sector's vulnerability to external shocks and environmental factors.

Overall, the results suggest that Serbian agriculture operates within a dual framework: it is externally competitive in terms of export performance, yet internally constrained by structural inefficiencies that limit its capacity for higher value-added production and long-term sustainable growth. Addressing these constraints through targeted structural reforms, increased investment, and improved policy design remains essential for enhancing the sector's competitiveness and resilience.

Since 2023, the budget of the Ministry of Agriculture, Forestry and Water Management (MAFWM) has exceeded RSD 100 billion. Over the previous decade, the share of the MAFWM budget in the national budget remained below 5.4%, while from 2023 onwards it has surpassed 6.7%. In 2024, the MAFWM budget reached RSD 125.7 billion, accounting for 6.74% of the national budget. According to Article 4, paragraph 3 of the Law on Incentives in Agriculture and Rural Development, this share cannot be lower than 5% of the national budget. Allocated funds are implemented through direct payments, rural development measures, specific incentives, IPARD support, and credit schemes. The largest portion of funds in 2024 (91%) was allocated through direct payments, with the following structure: crop production accounted for 56%, livestock production for 27%, and milk premiums for 16% (MAFWM, 2025).

The structure of agricultural budget expenditures reveals a pronounced concentration of support within direct payments, with a dominant allocation toward crop production. Such a distribution indicates a policy bias that reinforces the existing production structure, rather than promoting its transformation. The relatively lower share of support directed toward livestock production and rural development measures suggests limited effectiveness in addressing structural imbalances, particularly the underdevelopment of higher value-added activities. This allocation pattern may contribute to the persistence of low productivity and insufficient diversification within the agricultural sector.

The observed allocation structure raises important questions regarding the long-term effectiveness of agricultural policy. While direct payments contribute to income

stabilization, they may have limited capacity to stimulate technological modernization, productivity growth, and structural transformation. International experience suggests that greater emphasis on investment support, innovation adoption, rural development, and knowledge transfer mechanisms tends to generate more sustainable development outcomes. Therefore, the current structure of agricultural support in Serbia may require gradual adjustment toward measures that encourage higher value-added production and stronger competitiveness.

Consequently, a reorientation of public support toward investment measures, rural development programs, and value chain upgrading appears essential for fostering structural transformation, improving competitiveness, and enhancing the long-term sustainability of Serbian agriculture.

The strategy for agricultural development should be based on increasing the export of agri-food products through more intensive production, as well as on adjusting the production structure in line with effective demand, particularly for environmentally sustainable and organic food products with a higher degree of finalization (Mitrović et al., 2017). Agriculture should be supported in order to maximize the utilization of natural, human, and processing capacities. The effective use of agricultural potential is contingent upon the integration of small-scale producers into markets, enabling them to achieve higher profits and additional economic benefits (Zakić et al., 2014).

In Serbia, increases in agricultural product prices disproportionately benefit intermediaries, while primary producers capture the smallest share of gains (Marjanović, 2025). Within the overall value chain, farmers receive the lowest returns. Moreover, non-selective import practices crowd out domestic producers, despite the country's comparative advantages in agricultural production and its traditional role as a food exporter (Aničić et al., 2025). When considering value added per worker in agriculture, Serbia exhibits a persistent and substantial lag behind the European Union. This underscores the importance of implementing appropriate financing and investment policies aimed at technological upgrading, innovation, knowledge acquisition, and productivity growth (Dimitrijević et al., 2023).

Agricultural support measures are designed to ensure the stability of domestic food supply, increase sales and exports, and stimulate job creation within the sector (Kuzman et al., 2017).

Conclusions

The findings of this study indicate that the agricultural sector in Serbia possesses significant potential for further development, both in the segment of small-scale farms and among agribusiness enterprises. However, the country's comparative advantages remain underutilized, while the adoption of innovation and advanced knowledge, already widely implemented in developed EU countries, continues to lag behind, resulting in substantially weaker performance.

The empirical analysis confirms that the development constraints of Serbian agriculture are primarily structural in nature. Although the sector maintains a positive foreign trade balance and a significant share in total exports, these achievements have not been accompanied by proportional improvements in productivity, value-added generation, or technological modernization. The results reveal a persistent mismatch between the sector's resource potential and its actual economic performance.

Key structural constraints, including low productivity, limited access to financing, smaller average farm size, and an imbalanced production structure characterized by the dominance of crop production (two-thirds) over livestock production (one-third), highlight the need for a more effective and coherent agricultural policy framework.

Particular attention should be devoted to the long-term consequences of the existing production structure. The predominance of crop production, combined with the decline of livestock production, limits opportunities for higher value-added creation, stronger vertical integration, and greater resilience of the agri-food sector. At the same time, the export structure remains largely based on primary agricultural commodities, indicating insufficient development of processing capacities and higher stages of value creation.

There is a clear need for strategic and predictable measures. From a policy perspective, Serbia requires a more coherent, predictable and investment-oriented agricultural policy framework focused on improving access to finance, stimulating technological modernization, promoting farm consolidation, strengthening livestock production, and supporting innovation throughout the agri-food value chain. The recent increase in the share of agriculture in the national budget represents a positive signal toward fostering faster and more sustainable sectoral development.

The findings further suggest that future agricultural policy should place greater emphasis on investment support, technological upgrading, innovation adoption, knowledge transfer, and the development of higher value-added production. Such measures would contribute not only to productivity growth and improved competitiveness, but also to stronger integration into European and global value chains.

Such policy adjustments would not only enhance the competitiveness of market participants and improve foreign trade performance, but also contribute to mitigating rural depopulation and promoting more balanced regional development.

Ultimately, unlocking the full potential of Serbian agriculture requires a comprehensive approach focused on structural transformation, increased investment, technological upgrading, and stronger integration into higher value-added segments of the agri-food value chain.

The results of this research provide evidence that sustainable growth of Serbian agriculture will depend not only on the availability of natural resources and favorable production conditions, but also on the successful implementation of structural reforms capable of transforming comparative advantages into durable competitive advantages.

Conflict of interests

The authors declare no conflict of interest.

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PROCUREMENT MANAGEMENT SYSTEMS AND ASSESSMENT OF THE MODERNITY OF AGRICULTURAL PROCUREMENT PROCESSES

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ABSTRACT

This paper examines procurement management systems and the perceived modernity of agricultural procurement processes in Croatian companies. The research was conducted on a sample of 101 respondents from companies operating in agricultural production and related agri-food supply chains. Data were collected through a questionnaire and analyzed using descriptive statistics and analysis of variance. The results show that centralized and partially centralized procurement systems predominate, while decentralized systems are rarely used. Most respondents assess their procurement systems as partially modern, indicating room for further organizational and technological improvement. The analysis did not confirm statistically significant differences in the perceived modernity of procurement systems among small, medium-sized and large companies. The findings suggest that agricultural companies recognize the importance of procurement modernization, but that further investment in digital tools, process improvement and staff education is needed to strengthen procurement efficiency and competitiveness.

Introduction

Efficiency is analyzed through quantitative modelling and is represented by the financial indicators Order Cost, Administrative Cost, Lead Time Opportunity Cost and Opportunity Cost of Capital. The remaining five benefits (decentralisation, transparency, control, maverick-buying reduction, supply-base rationalisation) are

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related to organisational performance and assessed qualitatively (Ronchi et al., 2010). A comprehensive business case should include all direct costs for the services being provided as well as the indirect costs associated with managing the supplier–customer relationships and those incurred from risk management activities (Walker & Rowlinson, 2008). The procurement system, it was claimed by the contractors and the stakeholders, made selection based on cronyism, personal relationship rather than on professional standing. At that time, the tender board was seen as the ultimate decision-maker and nobody could contest their choice of selection. The procurement officers were blamed for malpractice and non-compliance with the policies and procedures of the procurement system (Shu Hui et al., 2011). The delivery method should have the following functions to achieve the owner's goal, including the time estimation as accurate as possible when signing the contract; incentive mechanisms to ensure the work of the planning, design, pre-construction preparation, construction, procurement stages be shortened (Alhazmi & McCaffer, 2000). Local purchasing units are typically better informed than the centre on the product characteristics that they need but sometimes may find it costly, or inconvenient, to transfer this information to the centre (Dimitri et al., 2006).

The impact of digitisation towards procurement has a positive character and organisations should take the future role of procurement and strategic network node into account when aligning its procedures and processes towards the digital strategy (Bienhaus & Haddud, 2018). E-procurement brings about important simplifications of the MRO procurement process and reduces this operational workload for buyers by decentralizing the operational procurement process (Puschmann & Alt, 2005). Cui et al., (2022) explored how a buyer's AI strategy would affect the wholesale price received from suppliers. By designing and conducting a randomized field experiment, they find that having a purely autonomous request-for-quotation process results in a higher price quote—that is, suppliers price-discriminate a not-so-smart chatbot buyer.

Literature review and hypothesis

Supplier selection, which sets out to choose adequate suppliers to whom services will be contracted-out; and supplier evaluation, which assesses the performance of suppliers who are already working with the company (de Araujo et al., 2017). One of the key changes to procurement directives is the need for "compulsory e-procurement" with fully electronic procurement, including the online submission of tenders, being required by June 2016. There is however a down side in this new initiative in that, the application of e-procurement platforms requires significant investment in both specialist software and staff training (Naoum & Egbu, 2015). The ability to „punch out" procurement order data into financial control systems is regarded as a critical requirement for the success of an e-procurement system and thus close integration with finance systems was identified as an important criteria (Croom & Brandon-Jones, 2005). Controlling for purchasing costs is also fundamental for private companies to compete in the global economy. Cost control is crucial for firms to remain in business when economies do not grow, or grow very little, since demand is likely to be weak and firms' revenues low (Dimitri et al.,

2006). Products based on sugar and chocolate can have the epithet of luxury products and the increase in prices has a statistically significant impact on the growth of demand (Mladenović et al., 2024). Procurement strategy should be developed that balances risk against the project objectives that are established at an early stage (Davis et al., 2008).

There is a strongly positive and statistically significant link between aspects of sustainable procurement that are oriented on environmental and labour health and safety and procurement from small and local businesses (Walker & Brammer, 2012). It is not only a problem to ensure an adequate volume of agricultural production for the normal functioning of the supply chain, but also to influence the prices of agricultural products (Dejanović, 2023).

Strategic supplier portfolio perspectives considering risks, trade-offs and interdependencies of relationships between the firm and its suppliers were developed (Wagner et al., 2013). A natural way to introduce moral hazard would be to allow for an initial, costly investment, which affects the distribution of quality. Since there is no screening mechanism to enable an uninformed buyer to distinguish among sellers who have invested in different levels of e, a trading mechanism only increases the likelihood that the seller will not actually be the end user of the product. The possibility of a trade exacerbates the incentive to shirk. A more general optimization problem can be constructed which takes this behavior into account but, of course, the linearity of the objective function disappears (Manelli & Vincent, 1995). Love et al. (1998) suggested that participants have to put aside their own objectives by considering the clients strategic project objectives in a holistic manner. This can be effectively achieved through the use of a project management organisation which acts as a control mechanism for the client and participants.

While the latter could be attributed to factors such as budgetary constraints and low levels of diffusion, it is somewhat concerning that the sample is heavily skewed towards technology that was adopted over a decade ago (McCue & Roman, 2012). Progress within the traditional procurement function can be slow to gain traction. For example, there can be varying levels of resistance to change and a reluctance to shift away from the existing systems, especially when investments create structural changes in business processes (Rejeb et al., 2018). It was widely acknowledged that there seems to be an internal politico-cultural glass ceiling preventing procurement professionals from being involved in organisation-wide business strategic decision-making (Tassabehji & Moorhouse, 2008). It may well be that corruption is higher in a more competitive environment. This is not to say that increases in competition are not desirable, as in fact they may be beneficial, but to highlight that a cost associated with tougher competition may be higher corruption and that it is reasonable to expect that corruption and competition will grow together in certain markets (Celentani & Ganuza, 2002). Starting with the overall model, it confirms that clients' desire to involve contractors in specification triggers them to perform cooperative procurement procedures (Eriksson & Pesamaa, 2007). Asker & Cantillon, (2010) characterize the optimal sequential procedure, i.e. the mechanism that maximizes the buyer's expected utility conditional on approaching suppliers at most once. Now that physical distances have become less important through reduced transportation costs and

fast communication, cultural and institutional distance can still be large (den Butter & Lins, 2008). Economic criteria such as payment conditions, i.e. the price of the product itself, as well as the supplier's willingness to negotiate, quick response to inquiries and complaints, as well as openness to stable cooperation, still play a major role (Nedeljković et al., 2025). Serious strategic procurement actively controls its costs, which in the case of energy means monitoring legal frameworks, subsidies, and energy prices in relevant markets.(Galić et al, 2024). Despite extensive research on procurement structures, limited empirical studies focus specifically on procurement systems within agricultural enterprises, particularly in transitional economies. This research aims to address that gap

For the purposes of establishing quality research and conclusions, basic hypothesis were set:

H1: Centralized purchasing systems are dominant in organizations compared to decentralized models.

Materials and methods

This research applied a scientific approach to analysis by deconstructing the concept of competitiveness into its basic components, including the competitive position of procurement, strategic orientation, relevance and effectiveness of procurement management, modernity of procurement systems, and level of employee motivation. Relations with suppliers and customers and the quality of cooperation with them were also analyzed, with special emphasis on the mutual interactions of these elements. In the process of generalizing the methodological frameworks used, specific aspects of competitiveness were considered within a broader context, with individual factors analyzed as interconnected wholes. For example, elements related to the competitive position of procurement were viewed as a single functional unit, while aspects related to suppliers, employee motivation, and other key variables were considered in a similar manner, in order to maintain analytical consistency. The research was specifically conducted among companies operating within agricultural production and related agri-food supply chains. The descriptive analysis method was applied to interpret the characteristics of the competitive position of procurement, relationships and levels of satisfaction in interactions with suppliers, and employee motivation. The following scientific methods were used in the research:

Survey – This method collected data on competitiveness from various aspects, with the respondents being company executives, procurement managers, and managers in the agricultural production sector. In addition, the survey collected data on the competitive position in the agricultural products market from the perspective of customers.

Scaling – The research applied the Likert rating scale, which is one of the most commonly used methods in the social sciences. This technique was implemented in questionnaires intended for procurement executives and managers. To achieve the research objectives and test the hypotheses related to the research, several statistical methods were applied with the aim of obtaining key statistical values. The selection of these methods was aligned with the characteristics of the defined variables, and data processing was carried out using IBM SPSS Statistics 20. For this purpose, the following statistical procedures and measures were applied:

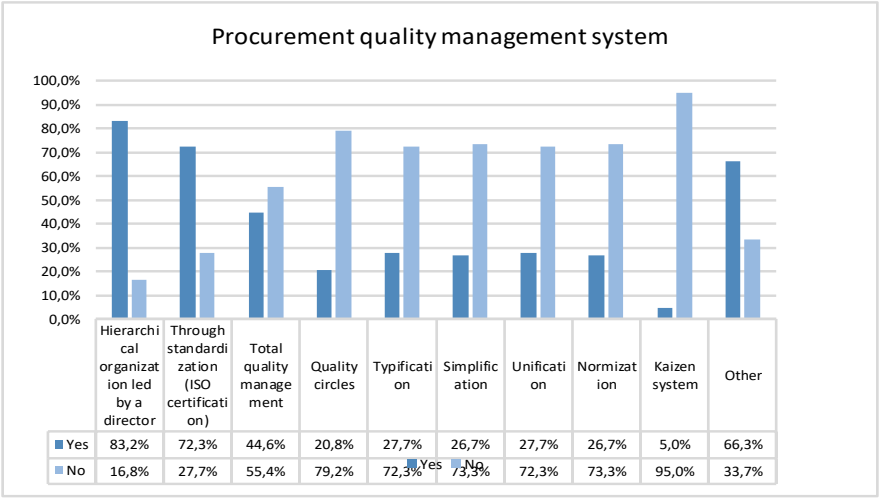
- Calculation of frequencies and shares (percentages)
- Descriptive statistics
- Measures of central tendency: arithmetic mean (M)
- Measures of variability: standard deviation (SD)
- Analysis of variance (ANOVA)
- Graphical and tabular presentation of results

In addition, histograms were used as a visual tool for displaying data arranged in certain categories or groups, which allowed the research results to be presented both graphically and in tabular form. The respondents were company executives, procurement managers, sales managers, and managers in the agricultural production sector. The sample consisted of 101 respondents.

Results and discussions

The findings provide insight into the structure of procurement systems within the agricultural sector. Surveyed companies predominantly utilize the hierarchically structured procurement quality management system (83.2%) and the procurement quality management system certified through standardization (ISO certificate) (72.3%). A minority of companies operate with comprehensive quality management systems which represent 44.6%. The Kaizen system is the procurement quality management system with the smallest representation at only 5%. The research examined both procurement system orientation and procurement system types with visual data presented in Figure 2. Figure 1 displays the results of an examination into various procurement quality management systems based on procurement system orientation.

Figure 1. Procurement quality management system

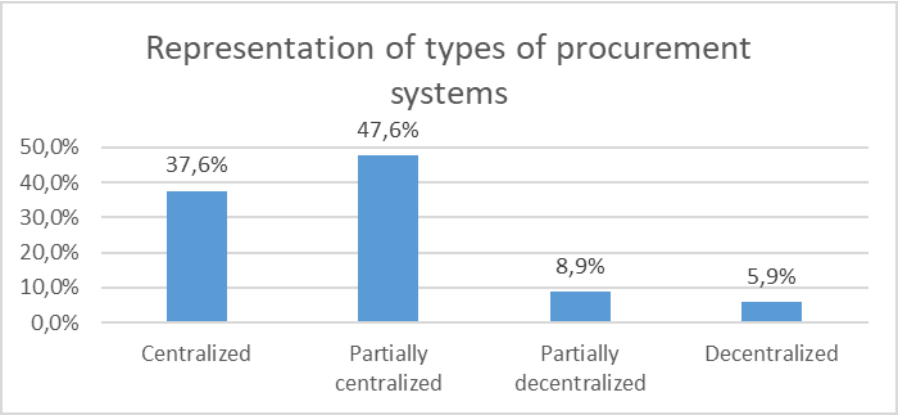


	Hierarchical organization led by a director	Through standardization (ISO certification)	Total quality management	Quality circles	Typification	Simplification	Unification	Normization	Kaizen system	Other
Yes	83,2%	72,3%	44,6%	20,8%	27,7%	26,7%	27,7%	26,7%	5,0%	66,3%
No	16,8%	27,7%	55,4%	79,2%	72,3%	73,3%	72,3%	73,3%	95,0%	33,7%

Source: Authors

The results indicate (Figure 1) that the most common procurement system is centralized (37.6%) and partially centralized (47.6%) compared to decentralized (5.9%) and partially decentralized (8.9%). Based on the results obtained, we can only conclude that the majority of the surveyed companies have a centralized and partially centralized procurement system, but we do not know which units are centralized and which are decentralized, and therefore we cannot make an assessment of whether the companies have desirable procurement systems. Both types of procurement systems have their advantages and disadvantages. We can say that the emphasis in the surveyed companies is on quality organization and compliance with rules and agreements. On the other hand, a smaller number of companies have a decentralized system, which is considered a more modern way of organization. A representation of the types of procurement systems by organization is shown in Figure 2.

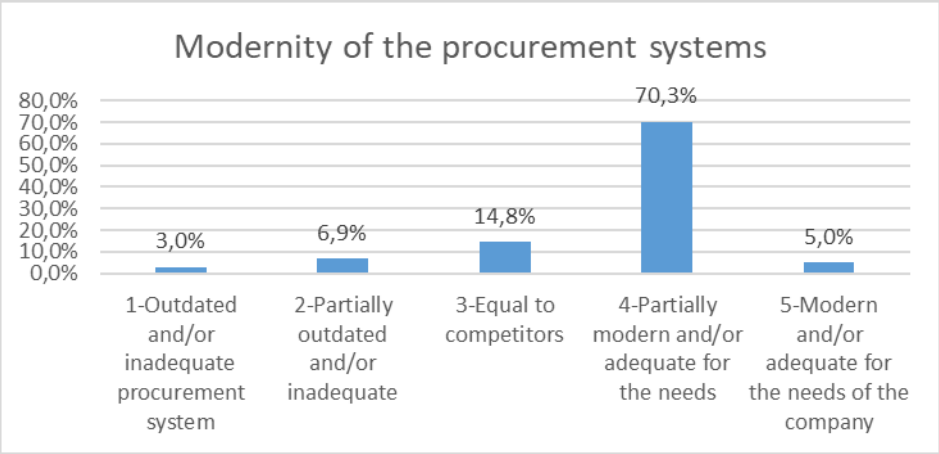
Figure 2. Representation of types of procurement systems



Source: Authors

Part of the competitiveness test also referred to the examination of the modernity of the procurement system, which was tested by a single statement to which the participants gave their assessments on a Likert-type scale of 1-5, where 1 means "outdated and/or inadequate procurement system" and 5 means "modern and/or adequate procurement system for the needs of society". The results are presented graphically using a histogram in Figure 3.

Figure 3. Modernity of the procurement systems of the surveyed companies



Source: Authors

In Figure 3, the majority of respondents consider their procurement system to be at least partially modern. Specifically, the largest share (70.3%) assesses their procurement system as "partially modern and/or adequate for the needs", while only 5% of respondents assess their system as fully modern and adequate for the needs of the company. Conversely, 3% of respondents consider their procurement system to be inadequate, while 6.9% state that it is partially outdated. Around 14.8% consider their system to be on par with their competitors. This data suggests that most companies recognize the need to modernize their procurement systems, although they rarely assess them to be fully optimal. Table 1. provides statistical analysis of communication with suppliers.

Table 1. Communication with suppliers

Contacts with suppliers/ customers are reduced to:	**Never**		**Rarely**		**Sometimes**		**Often**		**Always**		***Scale value***
	f	**%**	***f***	**%**	***f***	**%**	***f***	**%**	***f***	**%**	
1. Classic offer and sale of our services.	1	1	4	4	24	23.8	45	45.5	26	25.7	3.91
2. Invitation to regular meetings related to current and future cooperation.	1	1	8	7.9	21	20.8	43	43.6	27	26.7	3.87
3. To find out what suppliers/customers expect from us.	1	1	4	4	27	26.7	55	55.4	13	12.9	3.75
4. Communication exclusively via e-mail.	3	3	3	3	25	24.8	58	58.3	11	10.9	3.71
5. Encouraging suppliers/ customers to comment, give ideas.	2	2	7	6.9	26	25.7	49	49.5	16	15.9	3.70

Contacts with suppliers/ customers are reduced to:	Never		Rarely		Sometimes		Often		Always		*Scale value*
	f	*%*	*f*	*%*	*f*	*%*	*f*	*%*	*f*	*%*	
6. To interest them so that they decide to purchase the product as soon as possible.	2	2	6	5.9	26	25.7	53	53.5	13	12.9	3.69
7. To inform them about changes in business or the needs of the company.	2	2	8	7.9	30	30.7	39	38.6	21	20.8	3.68
8. Invitation to receptions and celebrations in the company.	2	2	13	12.9	26	25.7	49	49.5	10	9.9	3.52
9. Sending newsletters and other news related to the company to inform customers and suppliers.	8	7.9	9	8.9	24	24.7	44	43.6	15	14.9	3.49
10. Exchange of information about the way individual functions operate.	4	4	11	10.9	35	35.6	41	40.6	9	8.9	3.40

Source: Authors

The average assessment from participants regarding their communication with suppliers results in a score of 4 which corresponds to the frequency “often”. Most contacts with suppliers/customers consistently include traditional service offers (M=3.91) and scheduled meetings about ongoing partnerships (M=3.87) according to over 70% of participants. The majority of participants report that their interactions with suppliers/customers depend entirely on email communication (M=3.71; 69.2% of participants) to determine what suppliers/customers expect from them (M=3.75; 68.3%). The feedback on additional statements shows elevated ratings while more than half of participants express agreement.

The analysis of collected data reveals multiple important trends regarding how often suppliers are contacted. Findings revealed that the traditional offer and sale of services remains the primary interaction method with 45.5% of respondents using it frequently and 26% employing it all the time. The research suggests that traditional approaches maintain their significance in business partnerships. Regular meetings occur frequently as 27% of respondents always hold them and 43.6% hold them frequently. Commercial partnerships benefit greatly from organized processes and effective interpersonal communication.

The practice of motivating suppliers to share their ideas remains crucial to business partnerships since 49.5% of respondents do this often and 15% maintain this practice regularly. The data demonstrates cooperative openness but points to opportunities for improvement in this field. Respondents who always inform suppliers and customers about business changes amount to 20%, whereas 38.6% do so on a frequent basis. There is a portion of responders who only occasionally or never inform partners about business changes which puts trust and business connections at risk. Forty-

three point six percent of the respondents distribute company newsletters and other related material frequently according to the survey data while fifteen percent do it consistently. These are particularly low numbers. The findings reveal opportunities for better business relations with partners were missed together with a deficient internal communication strategy. 40.6% of respondents exchange information about individual functions operation frequently and only 9% always participate in this exchange. The limited frequency of information exchange creates negative effects on coordination and process efficiency in business operations. The research reveals that traditional methods of communication remain prevalent although digital engagement continues to grow in popularity. Businesses can enhance supplier-consumer collaboration by strengthening proactive information sharing and two-way communication practices. Table 2. presents descriptive data about supplier communication.

Table 2. Descriptive data for communication with suppliers with regard to the size of the company

	N	**M**	**SD**
Small companies	34	3.56	0.672
Medium companies	35	3.69	0.594
Large companies	32	3.78	0.423
Total	101	3.67	0.577

Source: Authors

Table 2 presents the mean score (M) and standard deviation (SD) metrics which reflect communication frequencies between companies of different sizes and their suppliers. Analysis reveals large companies maintain the highest average communication score at 3.78 and medium-sized companies follow with a score of 3.69, whereas small companies demonstrate the lowest mean score at 3.56. The study's outcome demonstrates that larger organizations engage in more intensive supplier communication because their supply chains necessitate more complex and regular interactions. Small companies demonstrate the greatest response variability as indicated by a standard deviation of 0.672 meaning that their communication with suppliers ranges widely between intensive contact and minimal interaction. Large companies demonstrate the lowest variability in their processes with an SD of 0.423 which reflects their structured communication methods. The ANOVA analysis results displayed in Table 3 examine the communication differences with suppliers between companies of various sizes.

Table 3. Differences in communication with suppliers based on company size

	df	**F**	**p**
Between groups	2	1.256	0.29
Within groups	98		
Total	100		

Source: Authors

The ANOVA analysis results presented in Table 3 investigate the significance of communication frequency variations between suppliers and firms of varying sizes. The F value of 1.256 and p-value of 0.29 demonstrate no statistically significant differences between groups since p exceeds the conventional significance threshold of 0.05. Larger companies communicate with suppliers more often than smaller ones but this difference does not reach a level of statistical significance. The differences between groups are not significant. This finding can be explained by multiple factors. The standardization of communication processes across firms might explain why smaller firms work to sustain regular supplier interactions to protect their supply stability. The findings suggest different communication approaches are present between firm types with larger firms favoring established processes and meetings whereas smaller firms depend more on spontaneous communication methods and personal relationships which the measurement scale fails to properly document. The limited frequency of meetings and needs surveys among respondents suggests that many companies lack strategic supplier relationship management approaches. Modern supply chain operations demonstrate the importance of quality and timely communication because they support business continuity while reducing risk and optimizing costs.

Discussion.

A hierarchically structured procurement management system operates in 83.2% of companies while procurement remains centralized in 37.6% of companies or partially centralized in 47.6%. Decentralized systems exist in only 5.9% of cases but grant business units flexibility to meet specific requirements suggesting that research into decentralization's effect on procurement agility holds promise. The survey results reveal that 70.3% of participants view their procurement system as partially modern whereas 5% identify their system as entirely modern. Within the agricultural sector, centralized procurement systems dominate due to the need for cost control and coordination of input purchasing. The findings demonstrate that organizations recognize modernization requirements while they also prepare to implement advanced procurement systems through digital means and e-procurement. The research identifies supplier communication as a fundamental research dimension. Traditional sales and meetings (M=3.91) remain the most popular communication methods but e-mail communication (M=3.71) continues to gain importance. While digital channels bring efficiency advantages, the overuse of e-mail communication can negatively impact supplier relations and create challenges during negotiations and market competition. . The assessment of the modernity of procurement systems shows that the majority of respondents, 70.3%, assess their procurement systems as partially modern and/or appropriate to the needs of the company. Only 5.0% of respondents consider their procurement system to be completely modern and appropriate to the needs of the company, while 3.0% of respondents assess the system as outdated and/or inappropriate. An additional 6.9% of respondents consider the system to be partially outdated, while 14.8% of respondents assess the system to be at the level of the competition. These results point to the conclusion that most companies do not consider

their procurement systems to be completely outdated, but at the same time they do not assess them as completely modern either. In other words, there is significant room for further modernization of procurement processes. Results related to communication with suppliers show that traditional forms of business communication are the most common. The highest average rating is given to the classic offer and sale of services, with a value of M = 3.91, followed by invitations to regular meetings related to existing and future cooperation, with a value of M = 3.87. Although the results show that larger companies communicate with suppliers on average somewhat more frequently and in a more structured manner, the analysis of variance did not confirm statistically significant differences between companies of different sizes. The obtained value was F = 1.256, with p = 0.29, which means that the differences are not statistically significant. Therefore, it can be concluded that company size in itself is not a decisive factor in the intensity of communication with suppliers. Based on the results presented, it can be concluded that the procurement systems in the observed companies are predominantly focused on centralization, control and standardization of processes. Such a model can contribute to better cost control, compliance of procedures and more efficient management of suppliers, but at the same time it can limit flexibility and faster adaptation to the specific needs of individual business units. The low prevalence of fully decentralized models, of only 5.9%, confirms that companies in the agricultural sector still give greater priority to stability and control over organizational flexibility.

Conclusion

The research conducted on a sample of 101 respondents provided insight into the characteristics of procurement management systems and an assessment of the modernity of procurement processes in companies operating in the field of agricultural production and related agri-food supply chains. The results show that in the observed companies, hierarchically structured procurement quality management systems are most prevalent, used by 83.2% of the surveyed companies, while the quality management system through standardization, or ISO certification, is present in 72.3% of the companies. Full quality management is present in 44.6% of the companies, while more modern and continuous development approaches, such as the Kaizen system, are present to a significantly lesser extent, or only in 5.0% of the surveyed companies. The research results confirm the pronounced dominance of centralized and partially centralized procurement systems. A fully centralized procurement system is used by 37.6% of the companies, while a partially centralized system is present in 47.6% of the companies. Taken together, centralized and partially centralized models make up 85.2% of the total sample. In contrast, partially decentralized systems are present in 8.9% of companies, and fully decentralized systems in only 5.9% of companies. This confirms hypothesis H1, according to which centralized procurement systems are more dominant than decentralized models. The research also shows that the modernization of procurement is not equally expressed in all observed aspects. On the one hand, most companies do not perceive their systems as outdated, which is confirmed by the fact that only 3.0% of respondents rate the system. The research has certain limitations that should be

considered when interpreting the results. The study was conducted on a sample of 101 respondents, which limits the possibility of generalizing the findings to all companies operating in the agricultural sector. In addition, the results are based on respondents' subjective assessments, especially regarding the perceived modernity of procurement systems, while objective indicators of digitalization, automation and financial effects of procurement modernization were not examined in detail.

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Conflict of interests

The authors declare no conflict of interest.

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DIGITAL MARKETING AND THE FINANCIAL PERFORMANCE OF AGROTOURISM IN RURAL AREAS: THE MODERATING ROLE OF SOCIOLOGICAL FACTORS

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A B S T R A C T

This paper examines the impact of digital marketing on the financial performance of agrotourism farms in rural areas, with particular emphasis on the moderating role of sociological factors. The empirical research was conducted during the first six months of 2026 using a structured questionnaire on a sample of 240 respondents. Digital marketing was analyzed through social media, online presence, online booking, online reputation, and digital advertising, while financial performance was assessed through revenue, profitability, occupancy rate, financial stability, and return on investment. Sociological factors included cooperation with the local community, guest recommendations, and the preservation of local tradition and authenticity. The data were analyzed using descriptive statistics, correlation analysis, regression analysis, and moderation regression analysis. The findings indicate that digital marketing is positively and statistically significantly associated with financial performance, while guest recommendations and the preservation of local authenticity strengthen this relationship.

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Introduction

Agrotourism represents one of the important forms of contemporary rural development, as it integrates agricultural production, tourism supply, local tradition, authentic experience, and the economic empowerment of rural households. In the context of increasing competition in the tourism market, agrotourism farms can no longer rely exclusively on traditional forms of promotion and direct contact with guests. Digital communication channels, social media, online booking systems, web presence, reviews, and digital advertising are becoming important instruments for market positioning and increasing the visibility of agrotourism offerings.

Digital marketing is of particular importance for agrotourism farms because it enables direct communication with potential guests, the presentation of authentic content, the promotion of local products, and a more efficient alignment of supply and demand. At the same time, the financial performance of agrotourism farms does not depend solely on their presence on digital platforms, but also on their ability to convert digital visibility into a higher number of reservations, more stable revenues, greater profitability, improved occupancy rates, and justified investment in promotion.

In addition to economic and marketing factors, agrotourism also has a pronounced sociological dimension. An agrotourism farm is not an isolated business entity, but rather a part of the local community, a network of social relations, trust, tradition, and the cultural identity of the rural environment. Therefore, this study pays particular attention to the sociological factors of agrotourism farms, namely cooperation with the local community, guest recommendations, and the preservation of local tradition and authenticity. These factors are examined as potential moderators of the relationship between digital marketing and financial performance.

The subject of this research is the analysis of the impact of digital marketing on the financial performance of agrotourism farms in rural areas, with an examination of the moderating role of sociological factors. The main objective of the paper is to determine whether digital marketing represents a significant predictor of the financial results of agrotourism farms, as well as whether cooperation with the local community, guest recommendations, and the preservation of local tradition and authenticity alter the strength of this relationship.

Literature Review

Agrotourism represents a specific form of rural tourism that integrates agricultural production, tourism services, local culture, authentic experience, and direct interaction between hosts and visitors. In contemporary literature, agrotourism is regarded as an important mechanism for the diversification of rural farms, as it enables additional sources of income, more efficient use of existing resources, and the strengthening of household economic resilience. Nickerson, Black, and McCool (2001) emphasize that one of the key reasons for the development of agrotourism is the need of farms and ranches to generate additional income beyond primary agricultural production. Tew and

Barbieri (2012) further underline that the benefits of agrotourism are not exclusively financial, but also include visitor education, the preservation of family farms, and stronger connections with the local community.

Agrotourism plays an important role in rural development, as it contributes to employment, the promotion of local products, the preservation of tradition, and the development of local communities. Previous studies indicate that agrotourism can contribute to income growth, improved market positioning of farms, and more sustainable development of rural areas (Barbieri & Mshenga, 2008; Khanal & Mishra, 2014; Liu et al., 2023; Turtureanu et al., 2025). Accordingly, in this study, the financial performance of agrotourism farms is examined through revenue, profitability, occupancy rate, financial stability, and return on investment.

Digital marketing has a specific role in agrotourism, as it enables farms to increase their visibility, communicate with guests, promote the authenticity of their offerings, and directly influence the decisions of potential visitors. Contemporary tourists increasingly search for information about rural destinations and farms through the internet, social media, online reviews, websites, and booking platforms. Buhalis and Law (2008) argue that information technologies have substantially transformed the functioning of tourism, while Rodrigues et al. (2023) show that digital marketing affects the image of rural destinations, visit intention, and destination sustainability. In this study, digital marketing is operationalized through five dimensions: the use of social media, online presence and visibility, online booking, online reputation and reviews, and digital advertising. Cvijanović and Ostojić (2026) emphasize that digital marketing in rural tourism contributes to destination promotion through social media, visual content and the communication of local authenticity, which supports the relevance of digital visibility in agrotourism.

Social media enables the visual presentation of farms, the promotion of experiences, and direct communication with guests. Online reviews, electronic word-of-mouth, and digital reputation represent important elements of contemporary tourism decision-making. Nilashi et al. (2022) show that eWOM on social media affects tourists' trust and the travel decision-making process. Similarly, Nguyễn (2025) indicates that electronic word-of-mouth influences trust, attitudes, destination image, and visit intention in the context of ecotourism. Cho et al. (2024) further confirm that online reviews have a significant effect on hotel demand. These findings are relevant to agrotourism because they demonstrate that the digital visibility of farms becomes more important when supported by positive online experiences, reputation, and guest trust. Xia et al. (2022) indicate that online hotel reviews significantly influence booking intention, while Tao et al. (2025) show that experiences presented in online reviews may shape tourists' perceptions and travel intentions. These findings further confirm that digital reputation and previous guests' experiences represent important decision-making factors in tourism, which is particularly relevant for agrotourism farms. Additional research confirms that online reviews and electronic word-of-mouth influence tourist decisions and bookings. Ruzima et al. (2024) show that online hotel reviews affect booking

intention, while Yu et al. (2024) indicate that the analysis of online reviews can identify tourists' needs and expectations. Akhi (2024) further confirms that eWOM influences tourists' travel intentions. These findings are significant for agrotourism because they suggest that previous guests' experiences and digital reputation may contribute to the decision to visit and to the selection of a particular farm.

The financial performance of agrotourism farms does not depend solely on the number of guests, but also on the ability of farms to convert digital visibility into bookings, revenue, and long-term business stability. In the literature, agrotourism is often considered a strategy for income diversification, particularly among small and family-owned farms. Arru et al. (2021), Pitrova et al. (2020), and Tafidou et al. (2023) indicate that diversification through agrotourism can contribute to the economic performance of farms. In this regard, digital marketing can be viewed as an instrument that enables the market potential of agrotourism offerings to be transformed into measurable financial effects.

In addition to economic and marketing factors, agrotourism has a pronounced sociological dimension. A farm is not an isolated business entity, but rather a part of the local community, a network of trust, tradition, local products, and social relations. For this reason, sociological factors are introduced in this study as moderating variables: cooperation with the local community, guest recommendations, and the preservation of local tradition and authenticity.

Cooperation with the local community can be theoretically linked to the concept of social capital. Social capital includes local networks, trust, cooperation, reciprocity, and collective action. Pramanik (2019) and Prayitno et al. (2024) emphasize that social capital plays an important role in community-based tourism, as it enables the connection of local actors and the development of sustainable tourism initiatives. In the context of agrotourism, cooperation with the local community may contribute to joint promotion, the inclusion of local products, and the strengthening of rural identity.

Guest recommendations represent another important sociological factor, as they reflect trust, reputation, and informal social influence. In tourism, recommendations from previous guests often have a stronger effect than formal promotion, since they originate from user experience. Phillips et al. (2013) demonstrated that satisfaction, value, and destination perception are associated with recommendations and revisit intention in rural destinations. Torabi et al. (2023) and Santos et al. (2023) indicate that digital technologies, revisit intention, and word-of-mouth play an important role in rural destinations. Therefore, in this study, guest recommendations are examined as a sociological moderator that may strengthen the effects of digital marketing on financial performance.

The third sociological factor is the preservation of local tradition and authenticity. Authenticity is particularly important for agrotourism because visitors often seek a direct experience of rural life, homemade food, local customs, tradition, and interaction with the host. Sims (2009) emphasizes that local food contributes to the sense of authenticity and sustainability of the tourism experience. Do (2025) shows that authenticity and sustainability influence visitors' experiences in farm-to-table agrotourism, while Fandos-

Herrera, Labuena, and Orús (2026) emphasize that authenticity and sustainability are key elements of rural tourism. Therefore, digital marketing may generate stronger effects when it promotes an authentic and locally embedded offering. Ostojić et al. (2025) show that green marketing supports sustainable rural tourism by connecting local resources, environmental responsibility and destination promotion, which is relevant for understanding the role of authenticity and community-based factors in agrotourism.

In this study, sociological factors are examined as moderators, based on the assumption that digital marketing does not operate in the same way across all farms. In farms with strong guest recommendations, digital promotion may be more persuasive because it is supported by social trust. In farms that preserve local tradition and authenticity, digital marketing may have a stronger effect because it promotes content that is differentiated, recognizable, and culturally grounded. In this way, the study integrates marketing, economic, and sociological perspectives in the analysis of the financial performance of agrotourism farms.

Materials and methods

The empirical research was conducted during the first six months of 2026 using a structured questionnaire administered to agrotourism farms in rural areas. The study is based on a quantitative approach, as numerically coded responses were used to examine the relationship between digital marketing, financial performance, and sociological factors of agrotourism farms.

The main objective of the research is to determine whether digital marketing represents a significant predictor of the financial performance of agrotourism farms, as well as whether selected sociological factors alter the strength of this relationship. Accordingly, the research includes one main independent variable, one dependent variable, and three moderating sociological variables.

The independent variable in the study is digital marketing. This variable includes activities used by agrotourism farms to increase visibility, communicate with guests, facilitate online bookings, manage reputation, and conduct digital advertising. Digital marketing was operationalized through five dimensions: the use of social media, online presence and visibility, online booking, online reputation and reviews, and digital advertising. This operationalization is based on contemporary studies indicating that digital channels, web analytics, online communication, and digital marketing activities may play an important role in improving market position, reducing advertising costs, increasing visibility, and strengthening the competitiveness of enterprises in the agri-food and tourism sectors (Kanellos et al., 2024; Cvjetković et al., 2026). This is particularly relevant because, through social media, online presence, and reputation management, agrotourism farms can communicate more directly with potential guests and increase the recognition of their offerings.

The dependent variable in the study is the financial performance of agrotourism farms. It was operationalized through five dimensions: revenue, profitability, occupancy rate,

financial stability, and return on investment. These dimensions were selected because agrotourism is not only a form of tourism activity, but also a mechanism for the economic diversification of rural households. Through the development of agrotourism offerings, farms can generate additional income, increase capacity utilization, improve financial stability, and reduce dependence on agricultural production alone. Previous studies indicate that agrotourism contributes to rural development, local income generation, employment, and the sustainability of rural communities (Liu et al., 2023; Turtureanu et al., 2025).

In addition to digital marketing and financial performance, sociological factors of agrotourism farms were also included in the research. These factors were examined as moderating variables, based on the assumption that certain social characteristics of farms may strengthen or weaken the relationship between digital marketing and financial performance. Sociological factors were operationalized through three binary categorical variables: cooperation with the local community, guest recommendations, and the preservation of local tradition and authenticity. These variables were measured using "yes" and "no" responses, with "yes" coded as 1 and "no" coded as 0.

It should be noted that financial performance was measured based on respondents' perceptions rather than objective accounting data. This approach was selected because many agrotourism farms are small or family-owned businesses and may not be willing or able to provide detailed financial records. Nevertheless, perception-based financial indicators provide useful insight into how farm representatives assess the economic effects of digital marketing in their business operations.

To test the first hypothesis, descriptive statistics, correlation analysis, and regression analysis were applied. Descriptive statistics were used to present the basic characteristics of the variables, correlation analysis was used to examine the associations between the dimensions of digital marketing and financial performance, while regression analysis was used to assess the predictive effect of digital marketing on the financial performance of agrotourism farms.

To test the second, third, and fourth hypotheses, moderation regression analysis was applied. Sociological factors, coded as binary variables, were included in the regression models through interaction terms. In this way, the study examined whether cooperation with the local community, guest recommendations, and the preservation of local tradition and authenticity alter the strength of the relationship between digital marketing and financial performance.

In accordance with the research objective, the following hypotheses were formulated:

H1: Digital marketing has a positive effect on the financial performance of agrotourism farms.

H2: Cooperation with the local community moderates the relationship between digital marketing and the financial performance of agrotourism farms.

H3: Guest recommendations moderate the relationship between digital marketing and the financial performance of agrotourism farms.

H4: The preservation of local tradition and authenticity moderates the relationship between digital marketing and the financial performance of agrotourism farms.

Results

Before analyzing the main research variables, the structure of the respondents and the basic characteristics of the agrotourism farms are presented in Table 1. This analysis provides insight into the socio-demographic profile of the respondents, their level of education, experience in agrotourism business activities, and the primary activity of the farms. These characteristics represent an important contextual basis for the subsequent interpretation of the relationships between digital marketing, financial performance, and sociological factors.

Table 1. Structure of Respondents and Basic Characteristics of Agrotourism Farms

Variable	Category	Frequency	Percentage Share
Gender of respondents	Male	78	32.5%
	Female	162	67.5%
Age of respondents	Up to 30 years	153	63.7%
	From 30 to 50 years	60	25.0%
	Over 50 years	27	11.3%
Level of education	Primary/secondary education	21	8.8%
	College/university education	174	72.5%
	Master's/doctoral degree	45	18.8%
Length of involvement in agrotourism business	Less than 3 years	111	46.3%
	From 3 to 10 years	81	33.8%
	More than 10 years	48	20.0%
Primary activity of the farm	Accommodation	48	20.0%
	Food production	48	20.0%
	Hospitality services	66	27.5%
	Recreational activities	33	13.8%
	Combined activities	45	18.8%

Source: Author's research

The results presented in Table 1 show that female respondents dominate the sample, accounting for 67.5%, while male respondents account for 32.5%. The largest share of respondents belongs to the age category of up to 30 years, representing 63.7% of the sample, which indicates a pronounced representation of the younger population. This finding is relevant because younger respondents may be more open to the use of digital communication channels, social media, and online booking systems.

The educational structure shows that the majority of respondents have college or university education, accounting for 72.5%, while 18.8% have a master's or doctoral degree. This structure indicates a relatively high educational level among the respondents, which may be important for understanding the application of contemporary marketing and digital tools in agrotourism business.

Regarding experience in agrotourism, 46.3% of respondents reported that they had been engaged in this activity for less than three years, while 33.8% had been involved for three to ten years, and 20.0% for more than ten years. This indicates that a substantial share of the farms represent relatively young business entities that are still in the stage of development and market positioning. In terms of primary activity, hospitality services are the most represented category, accounting for 27.5%, followed by accommodation and food production, each accounting for 20.0%. Combined activities account for 18.8%, while recreational activities account for 13.8%.

Overall, the structure of the sample indicates that the analyzed farms are predominantly associated with younger and more highly educated respondents, as well as with entities that are largely in the earlier stages of agrotourism business development. Such a sample profile is relevant for the study of digital marketing, since farms in the development stage may use digital tools as an important instrument for increasing visibility, attracting guests, and improving financial results.

The sociological factors of agrotourism farms are presented in Table 2. The analysis includes three binary variables: cooperation with the local community, guest recommendations, and the preservation of local tradition and authenticity. These variables play an important role in the study, as they provide insight into the social context in which agrotourism business activities take place.

Table 2. Sociological Factors of Agrotourism Farms

Sociological Variable	Category	Frequency	Percentage Share
Cooperation with the local community (LC)	Yes	123	51.2%
	No	117	48.8%
Guest recommendations (GR)	Yes	112	46.7%
	No	128	53.3%
Preservation of local tradition and authenticity (LTA)	Yes	162	67.5%
	No	78	32.5%

Source: Author's research

The results presented in Table 2 show that 51.2% of farms cooperate with the local community, while 48.8% do not engage in this form of cooperation. This finding indicates a relatively balanced distribution between farms that are integrated into local cooperation networks and those that operate more independently. Regarding guest recommendations, 46.7% of respondents stated that a significant number of guests arrive through recommendations, while 53.3% reported the opposite. The most prominent sociological factor is the preservation of local tradition and authenticity, which is present in 67.5% of the farms.

Overall, the results indicate that the authenticity of the rural offering is the most prevalent sociological factor, while cooperation with the local community and guest recommendations are present in approximately half of the analyzed farms. These findings provide a basis for further examination of their moderating role in the relationship between digital marketing and financial performance.

Descriptive statistics for the digital marketing and financial performance variables are presented in Table 3. All analyzed variables were measured on a scale from 1 to 5, where higher values indicate a stronger degree of respondents' agreement with the stated items. The results show that the mean scores of all variables are relatively high, indicating a positive perception of digital marketing and its financial effects in agrotourism business.

Table 3. Descriptive Statistics for Digital Marketing and Financial Performance Variables

Variable Code	Variable Name	N	Min	Max	Mean	Standard Deviation
DM1	Use of social media	240	1	5	3.920	0.805
DM2	Online presence and visibility	240	1	5	4.108	0.722
DM3	Online booking	240	1	5	4.070	0.758
DM4	Online reputation and reviews	240	1	5	4.127	0.905
DM5	Digital advertising	240	1	5	4.140	0.875
FP1	Revenue	240	1	5	4.031	0.740
FP2	Profitability	240	1	5	4.153	0.682
FP3	Occupancy rate	240	1	5	4.259	0.703
FP4	Financial stability	240	1	5	4.104	0.833
FP5	Return on investment	240	1	5	4.163	0.995

Source: Author's research

Among the digital marketing variables, the highest mean score was recorded for DM5 (M = 4.140; SD = 0.875), followed by DM4 (M = 4.127; SD = 0.905) and DM2 (M = 4.108; SD = 0.722). These results indicate that respondents particularly recognize the importance of digital advertising, online reputation, and online presence in the promotion of agrotourism farms. The lowest mean score within the digital marketing dimension was recorded for DM1 (M = 3.920; SD = 0.805). However, this value is still above the midpoint of the scale, indicating that the use of social media is also evaluated positively, although slightly less strongly compared with other digital marketing activities.

Among the financial performance variables, the highest mean score was recorded for FP3 (M = 4.259; SD = 0.703), indicating that respondents particularly emphasize the contribution of digital marketing to higher occupancy rates. High scores were also recorded for FP5 (M = 4.163; SD = 0.995) and FP2 (M = 4.153; SD = 0.682), suggesting that respondents also associate digital marketing with return on investment and profitability. The lowest mean score was recorded for FP1 (M = 4.031; SD = 0.740), although this result also indicates a positive perception of the impact of digital marketing on revenue.

The standard deviations range from 0.682 to 0.995, indicating a moderate dispersion of responses. The lowest variability was observed for FP2 (SD = 0.682), suggesting that respondents were relatively consistent in their view that digital marketing contributes to profitability. The highest variability was recorded for FP5 (SD = 0.995), indicating more pronounced differences in the assessment of return on investment in digital marketing.

The results of the descriptive statistics indicate that respondents perceive digital marketing as an important instrument for improving the financial performance of agrotourism farms. The effects on occupancy rate, profitability, and return on investment are particularly prominent, while all variables recorded mean values above 3.9, confirming a high level of positive perception of the analyzed factors.

The correlation analysis presented in Table 4 was used to examine the associations between the dimensions of digital marketing and the dimensions of financial performance of agrotourism farms. All correlations are positive and statistically significant at the $p < 0.01$ level, indicating that a higher level of digital marketing implementation is associated with a higher level of financial performance. Pearson's correlation coefficients range from 0.482 to 0.775, indicating moderate to strong positive relationships between the analyzed variables.

Table 4. Correlations Between the Dimensions of Digital Marketing and the Financial Performance of Agrotourism Farms

Variable	FP1	FP2	FP3	FP4	FP5
DM1	0.719**	0.775**	0.607**	0.687**	0.624**
DM2	0.727**	0.703**	0.709**	0.764**	0.629**
DM3	0.699**	0.743**	0.690**	0.669**	0.514**
DM4	0.482**	0.646**	0.599**	0.667**	0.602**
DM5	0.641**	0.754**	0.707**	0.671**	0.589**

Note: Correlation is statistically significant at the $p < 0.01$ level. N = 240.

Source: Author's research

The strongest correlation was found between DM1 and FP2 (r = 0.775), indicating that this dimension of digital marketing is most strongly associated with the profitability of farms. A high correlation was also recorded between DM2 and FP4 (r = 0.764), suggesting that online presence and visibility may play an important role in stabilizing financial operations. In addition, a strong and statistically significant correlation was identified between DM5 and FP2 (r = 0.754), confirming that digital advertising is strongly associated with the profitability of agrotourism farms.

The weakest, although still statistically significant, correlation was recorded between DM4 and FP1 (r = 0.482). This result indicates that the association between online reputation and reviews and revenue is present, but weaker compared with the other analyzed relationships. A relatively weaker correlation was also observed between DM3 and FP5 (r = 0.514), as well as between FP3 and FP5 within the broader correlation pattern. This may indicate that online bookings and occupancy rates do not necessarily translate directly into return on investment, as this relationship may depend on promotional costs, pricing structure, and the seasonality of business operations.

The presented results of the correlation analysis provide strong empirical support for the basic assumption that the dimensions of digital marketing are positively associated with the financial performance of agrotourism farms. The relationships with profitability, financial stability, and return on investment are particularly notable,

indicating that digital marketing functions not only as a promotional tool, but also as a factor contributing to the improvement of farms' economic performance.

Regression analysis was applied to determine the predictive contribution of individual dimensions of digital marketing to explaining the financial performance of agrotourism farms. Unlike correlation analysis, which indicates the degree of association between variables, regression analysis provides insight into which dimensions of digital marketing make a statistically significant independent contribution to explaining specific aspects of financial performance. The table 5 presents only statistically significant predictors, while non-significant variables were omitted for the sake of clarity and readability of the results.

Table 5. Results of the Regression Analysis of the Effects of Digital Marketing Dimensions on Financial Performance

Dependent Variable	Independent Variable	β	t	Sig.	R^2	F	Sig.
FP1	DM1	0.316	4.544	0.000	0.626	78.211	0.001
	DM2	0.358	5.052	0.000			
FP2	DM1	0.306	5.136	0.000	0.725	123.421	0.001
	DM3	0.195	3.199	0.002			
	DM4	0.169	3.680	0.000			
	DM5	0.292	5.184	0.000			
FP3	DM2	0.235	3.299	0.001	0.621	76.604	0.001
	DM3	0.275	3.849	0.000			
	DM4	0.161	2.986	0.003			
	DM5	0.309	4.672	0.000			
FP4	DM2	0.404	6.079	0.000	0.671	95.391	0.001
	DM4	0.255	5.073	0.000			
FP5	DM1	0.327	4.145	0.000	0.520	50.628	0.001
	DM2	0.283	3.530	0.001			
	DM4	0.283	4.662	0.000			

Note: The table presents only statistically significant predictors. Predictors that were not statistically significant were excluded from the table. The β values represent standardized beta coefficie

Source: Author's research

The results show that all regression models are statistically significant, as confirmed by the F-test values and the significance level of $p < 0.001$. This indicates that the dimensions of digital marketing jointly represent significant predictors of all analyzed dimensions of financial performance. The coefficients of determination range from $R^2 = 0.520$ for FP5 to $R^2 = 0.725$ for FP2, indicating that the models explain between 52.0% and 72.5% of the variance in financial performance. These values represent a high level of explained variance and indicate a strong contribution of digital marketing to the financial results of agrotourism farms.

The highest level of explained variance was recorded in the model for FP2, where $R^2 = 0.725$. This means that the dimensions of digital marketing explain 72.5% of the variability in this financial dimension. DM1, DM3, DM4, and DM5 emerged as significant predictors, with the highest standardized beta coefficient recorded for DM1 ($\beta = 0.306$), followed by DM5 ($\beta = 0.292$). This result indicates that this financial dimension particularly depends on the combined effect of several digital activities, including digital communication, online booking, reputation, and digital advertising.

In the FP4 model, 67.1% of the variance is explained, with DM2 and DM4 identified as statistically significant predictors. The strongest predictor is DM2 ($\beta = 0.404$; $p < 0.001$), indicating that online presence and visibility play a particularly important role in explaining this dimension of financial performance. DM4 also makes a significant contribution ($\beta = 0.255$; $p = 0.000$), confirming that online reputation and reviews represent important factors of financial stability and market reliability for agrotourism farms.

The model for FP1 explains 62.6% of the variance, with DM1 and DM2 identified as significant predictors. DM2 makes a stronger contribution ($\beta = 0.358$; $p = 0.001$), while DM1 is also a strong and statistically significant predictor ($\beta = 0.316$; $p = 0.001$). This result shows that farm revenue is particularly associated with digital visibility and the active use of digital channels for promotion and communication with potential guests.

For FP3, the R^2 value is 0.621, meaning that digital marketing explains 62.1% of the variance in this financial dimension. DM2, DM3, DM4, and DM5 emerged as significant predictors, with the strongest contribution made by DM5 ($\beta = 0.309$; $p = 0.000$), followed by DM3 ($\beta = 0.275$; $p < 0.001$). This finding indicates that digital advertising and online booking are particularly important for explaining FP3, which is expected given that digital channels directly affect the availability of the offer, guest attraction, and capacity utilization.

The lowest, although still high, percentage of explained variance was recorded for FP5, where $R^2 = 0.520$. The significant predictors are DM1, DM2, and DM4, with the strongest contribution made by DM1 ($\beta = 0.327$; $p = 0.001$), while DM2 and DM4 have identical standardized beta values ($\beta = 0.283$). This result shows that return on investment in digital marketing is most strongly associated with the active use of digital channels, online visibility, and the farm's reputation.

The results of the regression analysis confirm that digital marketing has a significant and strong predictive effect on the financial performance of agrotourism farms. DM2 and DM4 are particularly notable, as they appear as significant predictors in four out of five models. This indicates that online presence, visibility, and reputation are key elements of digital marketing in the context of the financial performance of agrotourism farms. Based on the obtained results, it can be concluded that the first research hypothesis is supported, since the dimensions of digital marketing statistically significantly explain all analyzed dimensions of financial performance.

After examining the direct effect of digital marketing on the financial performance of agrotourism farms, moderation regression analysis was conducted to determine

whether sociological factors alter the strength of this relationship. Three sociological variables were included in the analysis: cooperation with the local community, guest recommendations, and the preservation of local tradition and authenticity. Interaction terms are of particular importance in these models, as they indicate whether a specific sociological factor has a moderating role.

Table 6 presents the results of the moderation regression analysis for the second hypothesis, which examined whether cooperation with the local community moderates the relationship between digital marketing and the financial performance of agrotourism farms. The model is statistically significant, $F = 406.409$; $p < 0.001$, with an R^2 value of 0.838. This means that the included predictors explain 83.8% of the variance in overall financial performance, representing a very high level of explained variance.

Table 6. Results of the Moderation Regression Analysis for H2

Dependent Variable	Independent Variable	β	t	Sig.	R^2	F	Sig.
FP_TOTAL	LC	-0.152	-0.972	0.332	0.838	406.409	0.001
	DM_TOTAL	0.893	23.803	0.001			
	INTLC	0.117	0.747	0.456			

Source: Author's research

Within the model, digital marketing has a strong and statistically significant positive effect on financial performance, $\beta = 0.893$; $t = 23.803$; $p < 0.001$. This result confirms that the overall level of digital marketing is one of the key predictors of the financial performance of agrotourism farms. Conversely, the direct effect of cooperation with the local community is not statistically significant, $\beta = -0.152$; $t = -0.972$; $p = 0.332$. This indicates that the mere fact that a farm cooperates with the local community does not significantly contribute to explaining financial performance when digital marketing is included in the model.

The key indicator for testing the second hypothesis is the interaction term INTLC, which represents the product of digital marketing and cooperation with the local community. The results show that this interaction effect is not statistically significant, $\beta = 0.117$; $t = 0.747$; $p = 0.456$. Since the p-value is greater than 0.05, it can be concluded that cooperation with the local community does not significantly alter the strength of the relationship between digital marketing and financial performance.

Table 7 presents the results of the regression analysis for the third hypothesis, which examined the role of guest recommendations in the relationship between digital marketing and the financial performance of agrotourism farms. The model is statistically significant, $F = 35.405$; $p < 0.001$, while the R^2 value is 0.310. This means that the model explains 31.0% of the variance in financial performance.

Table 7. Results of the Moderation Regression Analysis for H3

Dependent Variable	Independent Variable	β	t	Sig.	R^2	F	Sig.
FP_TOTAL	DM_TOTAL	-0.063	-1.174	0.242	0.310	35.405	0.001
	GR	-2.504	-9.845	0.001			
	INTGR	2.593	10.193	0.001			

Source: Author's research

The results show that the main effect of digital marketing is not statistically significant in this interaction model, β = -0.063; t = -1.174; p = 0.242. This means that, when guest recommendations and the interaction term are included in the model, digital marketing does not make a significant independent contribution to explaining financial performance. However, this result should not be interpreted in isolation, because the interaction term is statistically significant.

The most important result for testing the third hypothesis refers to the interaction term INTGR. The results show that the interaction is statistically significant, β = 2.593; t = 10.193; p = 0.001. This means that guest recommendations have a significant moderating role in explaining financial performance. In other words, the effect of digital marketing on financial performance differs depending on whether a significant number of guests arrive through recommendations from previous guests.

Table 8 presents the results of the regression analysis for the fourth hypothesis, which examined whether the preservation of local tradition and authenticity moderates the relationship between digital marketing and the financial performance of agrotourism farms. The model is statistically significant, F = 130.650; p = 0.001, with an R^2 value of 0.624. This means that the model explains 62.4% of the variance in financial performance, representing a high level of explained variance.

Table 8. Results of the Moderation Regression Analysis for H4

Dependent Variable	Independent Variable	β	t	Sig.	R^2	F	Sig.
FP_TOTAL	DM_TOTAL	-0.015	-0.363	0.717	0.624	130.650	0.001
	LTA	-2.745	-19.549	0.001			
	INTLTA	2.735	19.441	0.001			

Source: Author's research

The main effect of digital marketing is not statistically significant in this interaction model, β = -0.015; t = -0.363; p = 0.717, indicating that it does not make a significant independent contribution when the preservation of local tradition and authenticity and the interaction term are included in the model. The variable LTA, which refers to the preservation of local tradition and authenticity, shows a statistically significant effect, β = -2.745; t = -19.549; p < 0.001. As in the previous model, the negative sign of the beta coefficient should be interpreted with caution, particularly due to the binary coding of the variable and the presence of the interaction term.

The key result for testing the fourth hypothesis is the interaction term INTLTA. The results show that this effect is statistically significant, $\beta = 2.735$; $t = 19.441$; $p < 0.001$. This means that the preservation of local tradition and authenticity statistically significantly moderates the relationship between digital marketing and the financial performance of agrotourism farms. In other words, the effect of digital marketing on financial performance is not the same among farms that base their offerings on local tradition and authenticity and those in which this factor is not present.

The results of the moderation regression analysis show that sociological factors do not have an equal role in explaining the relationship between digital marketing and the financial performance of agrotourism farms. Cooperation with the local community was not confirmed as a significant moderator, since the interaction effect INTLC was not statistically significant. In contrast, guest recommendations and the preservation of local tradition and authenticity showed statistically significant interaction effects, indicating that these two factors alter the strength of the relationship between digital marketing and financial performance.

These findings suggest that digital marketing generates the strongest effects when it is connected with elements of trust, reputation, and authenticity. Guest recommendations represent social proof of service quality, while local tradition and authenticity represent the substantive foundation of the agrotourism offering. In this sense, digital marketing does not operate in isolation; rather, its effects depend on the social and cultural context in which the farm conducts its business.

Discussion

The results of the conducted research confirm that digital marketing plays a significant role in explaining the financial performance of agrotourism farms. Descriptive statistics showed relatively high mean scores for all dimensions of digital marketing and financial performance, indicating that respondents recognize digital channels, online presence, online reputation, booking systems, and digital advertising as important instruments of contemporary agrotourism business. This finding is particularly relevant given the structure of the sample, which is predominantly composed of younger and more highly educated respondents, suggesting a potentially greater openness to the use of digital technologies in agrotourism operations.

The positive and statistically significant relationships between digital marketing dimensions and financial performance dimensions provide strong empirical support for the importance of digital marketing in agrotourism. The regression models explained a high proportion of variance in financial performance, which indicates that digital marketing contributes not only to the visibility of agrotourism farms, but also to their economic outcomes. These findings are consistent with Buhalis and Law (2008), who emphasized that information technologies have substantially transformed the tourism sector, as well as with Rodrigues et al. (2023), who confirmed the importance of digital marketing for rural destination image, visit intention, and sustainability. The present

study extends these findings by showing that digital marketing is also associated with concrete financial outcomes of agrotourism farms, including revenue, profitability, occupancy rate, financial stability, and return on investment. Therefore, the first research hypothesis, which stated that digital marketing has a positive effect on the financial performance of agrotourism farms, is supported.

The results further indicate that online presence and visibility, as well as online reputation and reviews, repeatedly appeared as significant predictors across several regression models. This suggests that the financial performance of agrotourism farms does not depend merely on their presence on digital platforms, but also on the quality of online presentation, the availability of information, the visibility of the offer, and the trust developed through online reviews. This finding is in line with Nilashi et al. (2022), Nguyễn (2025), Cho et al. (2024), Xia et al. (2022), and Ruzima et al. (2024), who emphasize the importance of electronic word-of-mouth, online reviews, trust, and digital reputation in tourism decision-making and booking behavior. In the context of agrotourism, these elements are particularly important because guest decisions are often based on expected experience, authenticity, and trust in the host.

The moderating role of cooperation with the local community was not statistically confirmed. Although the overall moderation model was statistically significant, the interaction effect between digital marketing and cooperation with the local community was not significant. This indicates that cooperation with the local community did not significantly strengthen or weaken the relationship between digital marketing and financial performance in the analyzed model. This result does not imply that local community cooperation is irrelevant for agrotourism. Previous studies on social capital and community-based tourism, such as Pramanik (2019) and Prayitno et al. (2024), emphasize the importance of local networks, trust, cooperation, and collective action for sustainable tourism development. However, the findings of the present study suggest that the effects of community cooperation may be more indirect and long-term, related to social cohesion, rural identity, destination sustainability, and the broader development of the local environment, rather than to immediate financial performance. In addition, the binary measurement of this variable may not have sufficiently captured the intensity, quality, and continuity of cooperation with local actors. Accordingly, the second research hypothesis, which assumed that cooperation with the local community moderates the relationship between digital marketing and financial performance, is not supported.

Unlike cooperation with the local community, guest recommendations showed a statistically significant moderating effect. This result indicates that the relationship between digital marketing and financial performance becomes stronger when a significant number of guests arrive through recommendations from previous visitors. Such a finding confirms the importance of social trust, reputation, and informal communication in agrotourism. It is consistent with Phillips et al. (2013), who showed that satisfaction, perceived value, and destination perception are associated with recommendations and revisit intention in rural tourism. It is also in line with Torabi et al. (2023) and Santos et al. (2023), who emphasized the role of word-of-mouth,

digital technologies, and revisit intention in rural destinations. In this context, digital marketing appears to generate stronger financial effects when it is supported by positive guest experiences and recommendations. Therefore, the third research hypothesis, which stated that guest recommendations moderate the relationship between digital marketing and the financial performance of agrotourism farms, is supported.

The preservation of local tradition and authenticity also proved to be a statistically significant moderator. The results indicate that authenticity, local customs, homemade food, and the rural way of life strengthen the financial effectiveness of digital marketing. This finding is consistent with Sims (2009), who emphasized the importance of local food for authentic and sustainable tourism experiences, as well as with Do (2025), who showed that authenticity and sustainability shape visitor experiences in farm-to-table agrotourism. The result is also aligned with Fandos-Herrera, Labuena, and Orús (2026), who identified authenticity and sustainability as key elements of rural tourism. In this sense, digital marketing has the greatest effect when it promotes content that is locally embedded, culturally recognizable, and authentic. Therefore, the fourth research hypothesis, which assumed that the preservation of local tradition and authenticity moderates the relationship between digital marketing and financial performance, is supported.

Taken together, the findings indicate that digital marketing has a direct and strong effect on the financial performance of agrotourism farms, confirming H1. Sociological factors, however, do not have an equal moderating role. Cooperation with the local community was not confirmed as a significant moderator, meaning that H2 is not supported. In contrast, guest recommendations and the preservation of local tradition and authenticity were confirmed as significant sociological moderators, supporting H3 and H4. These results suggest that the financial effects of digital marketing are strongest when digital visibility is combined with trust, reputation, guest satisfaction, and authentic rural content. Therefore, digital marketing in agrotourism should not be understood only as a promotional instrument, but as a mechanism whose effectiveness depends on the social and cultural context in which the farm operates.

Conclusions

The research results show that digital marketing plays a significant role in the financial performance of agrotourism farms. Correlation and regression analyses confirmed that the dimensions of digital marketing are positively and statistically significantly associated with revenue, profitability, occupancy rate, financial stability, and return on investment. This confirms that digital marketing represents an important predictor of the financial performance of agrotourism business.

The moderation analysis showed that sociological factors do not have an equal role in this relationship. Cooperation with the local community was not confirmed as a statistically significant moderator, whereas guest recommendations and the preservation of local tradition and authenticity showed significant moderating effects. This indicates that digital marketing generates stronger financial effects when supported by guest trust, positive recommendations, and an authentic rural offering.

The theoretical contribution of the paper lies in linking digital marketing, financial performance, and sociological factors within a single research model. From a practical perspective, the results indicate that agrotourism farms should develop their digital presence while simultaneously strengthening their reputation, encouraging guest recommendations, and preserving local identity as a basis for market differentiation.

The limitations of the research relate to the binary measurement of sociological factors, since "yes" and "no" responses do not capture the intensity, quality, or continuity of cooperation, recommendations, or the preservation of tradition. In addition, financial performance was measured based on respondents' perceptions rather than objective financial indicators.

Future research should include objective data on revenue, number of bookings, occupancy rates, and investments in digital marketing. Furthermore, the use of more detailed scales for measuring sociological factors is recommended, as well as a longitudinal approach that would enable the effects of digital marketing to be monitored across several tourism seasons.

Conflict of interests

The authors declare no conflict of interest.

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THE ROLE OF AGRICULTURAL STRUCTURE IN ECONOMIC CONVERGENCE: EVIDENCE FROM EUROPEAN UNION AND WESTERN BALKAN ECONOMIES

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ABSTRACT

This study examines whether agricultural structure and institutional quality influence economic convergence across European Union and Western Balkan economies between 2004 and 2023. The analysis uses a panel dataset covering 32 countries and applies fixed-effects estimation with robust standard errors to evaluate the relationship between initial income, agricultural structure, institutional quality, and economic growth. The findings provide evidence of conditional convergence and show that the share of agriculture in the economy does not exert a robust or systematic effect on growth once institutional quality is considered. In contrast, institutional quality consistently explains differences in economic performance, while structural composition does not significantly affect the speed of convergence. These results indicate that institutional development plays a more important role than agricultural structure in shaping convergence outcomes. The findings suggest that policies promoting institutional improvement should accompany structural transformation to support long-term convergence. The study contributes additional evidence from 32 European economies over the period 2004–2023.

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Introduction

Economic convergence represents a central concept in growth theory and remains a key policy objective within the European integration process. The expectation that less developed economies gradually catch up with more advanced ones has long been rooted in the neoclassical growth framework, where diminishing returns to capital generate convergence dynamics under relatively similar structural conditions. However, empirical evidence across European economies suggests that convergence is neither uniform nor automatic, but instead reflects a complex interaction of structural, institutional, and historical factors.

In the European context, successive waves of integration and enlargement have brought together economies with substantial differences in income levels, institutional capacity, and economic structure. While earlier empirical studies documented convergence among relatively homogeneous groups of economies, more recent research highlights increasing heterogeneity in convergence paths, particularly when comparing EU core economies, newer member states, and Western Balkan countries. These findings have led to a growing emphasis on conditional convergence frameworks, where structural and institutional characteristics play a central role in shaping long-run growth trajectories.

A substantial body of literature has examined the role of institutions as a determinant of economic performance. Institutional quality - captured through governance effectiveness, regulatory quality, and rule of law - has been consistently associated with higher levels of income and more stable growth patterns. However, recent empirical contributions suggest that institutions primarily influence growth outcomes rather than directly accelerating the speed of convergence. In this sense, institutions function as conditioning factors that shape the environment within which convergence occurs, rather than as mechanisms that fundamentally alter convergence dynamics.

At the same time, the structural composition of the economy has received comparatively less attention in the convergence literature, particularly within a unified European panel setting. Structural transformation, often characterized by a declining share of agriculture and a shift toward industry and services, represents a fundamental aspect of economic development. Economies with higher agricultural shares are typically associated with lower productivity levels, slower capital accumulation, and different growth dynamics compared to more diversified economies. This raises the question of whether structural composition, alongside institutional quality, contributes to explaining differences in convergence patterns across European economies.

Building on previous research on economic and institutional convergence in Europe, this paper extends the analysis by explicitly incorporating structural characteristics into the empirical framework. Earlier contributions have shown that institutional quality plays an important role in shaping growth differences across European economies, while its impact on convergence speed remains limited. In addition, recent findings indicate that institutional volatility and governance instability may affect growth dynamics in a heterogeneous manner across development stages. These insights provide a basis for

examining whether structural factors, such as the relative importance of agriculture, add explanatory power to the convergence framework.

The objective of this study is therefore to assess whether structural transformation, proxied by the share of agriculture in GDP, contributes to explaining economic convergence in Europe, and whether its effects remain robust once institutional factors are taken into account. The empirical analysis is conducted on a panel dataset covering 32 European economies over the period 2004-2023, encompassing EU core countries, new member states, and Western Balkan economies. The methodology follows a standard panel convergence approach, complemented by interaction terms and robustness checks to capture potential heterogeneity in growth dynamics.

The contribution of the paper is modest and incremental. Rather than introducing a new methodological framework, the study integrates structural and institutional dimensions within an established convergence setting. By doing so, it provides additional empirical evidence on the relative importance of economic structure and institutional quality in shaping growth outcomes across European economies. The results are consistent with previous findings suggesting that convergence processes are conditional, heterogeneous, and strongly influenced by institutional environments.

The remainder of the paper is organized as follows. The next section reviews the relevant literature. The following sections describe the materials, data, and methodology, present the empirical results, discuss the findings, and conclude the paper.

Literature Review

The theoretical foundations of economic convergence originate in the neoclassical growth framework, which predicts that economies converge toward their steady-state income levels due to diminishing returns to capital (Solow, 1956; Swan, 1956). This framework was subsequently formalized through the concept of β-convergence, where poorer economies are expected to grow faster than richer ones (Barro & Sala-i-Martin, 1992, 2004). Extensions of the model incorporating human capital and structural heterogeneity led to the concept of conditional convergence, where economies converge toward different steady states depending on underlying structural characteristics (Islam, 1995; Mankiw et al., 1992). Empirical panel-data approaches further refined these findings by controlling for unobserved heterogeneity and improving the robustness of convergence estimates (Baltagi, 2021; M. Hashem Pesaran, 2007).

Within the European context, convergence has been closely associated with economic integration and successive waves of EU enlargement. Early empirical evidence suggested that integration processes, including trade liberalization and capital mobility, supported convergence among member states (Boldrin & Canova, 2001; Crespo Cuaresma et al., 2008). However, subsequent research has emphasized persistent heterogeneity in convergence patterns, particularly following the 2004 enlargement (Borsi & Metiu, 2015; Bongardt & Torres, 2016). More recent studies highlight the emergence of a "multi-speed Europe," where convergence occurs within groups of countries but

not uniformly across the entire region (European Commission, 2022; OECD, 2020). These findings suggest that convergence in Europe is conditional, heterogeneous, and sensitive to both structural and institutional factors (Fingleton & López-Bazo, 2006).

A growing body of literature identifies institutions as a key determinant of long-run economic performance. Institutions shape economic incentives, reduce uncertainty, and influence investment and productivity (North, 1990; Acemoglu et al., 2001; Rodrik et al., 2004). Empirical evidence consistently shows that governance quality, regulatory effectiveness, and rule of law are positively associated with economic growth and income levels (Glaeser et al., 2004; Kaufmann et al., 2011). In the European context, institutional quality has become increasingly important following integration processes, as differences in governance structures contribute to divergent growth outcomes across countries (Campos & Coricelli, 2002).

Recent empirical contributions further refine the understanding of the institutional–convergence nexus. Evidence suggests that institutional quality plays a significant role in shaping growth differentials across countries, but its effect on the speed of convergence remains limited. In particular, institutions appear to influence steady-state income levels rather than systematically altering the β-convergence parameter (Lalić & Trifunović, 2026a, 2026b). This interpretation is consistent with findings showing that institutional variables often lose significance in interaction terms, indicating that their primary role is to condition growth rather than directly accelerate convergence processes (Lalić & Trifunović, 2026a).

Further evidence suggests that institutional effects may exhibit nonlinear or heterogeneous patterns across development stages. While some studies identify potential threshold dynamics, empirical support for strong regime-dependent effects remains limited. Instead, institutions appear to operate as gradual conditioning mechanisms that influence the stability and resilience of growth processes (Beyaert et al., 2019; Lalić & Trifunović, 2026d). Complementary research on institutional volatility indicates that instability in governance frameworks may negatively affect economic performance, particularly through increased uncertainty and reduced policy credibility (Klomp & de Haan, 2009; Lalić & Trifunović, 2026c).

Parallel to the institutional literature, a substantial body of research emphasizes the importance of structural factors in shaping economic growth and convergence. Structural transformation, typically characterized by a declining share of agriculture and an expansion of industry and services, represents a fundamental component of economic development (Chenery, H. B., & Syrquin, M., 1975; S. Kuznets, 1971). Economies with a higher share of agriculture are generally associated with lower productivity levels, limited technological diffusion, and slower growth dynamics (Temple, 1999). Empirical studies suggest that structural change plays a key role in explaining cross-country income differences and long-term development trajectories (Berthold Herrendorf et al., 2014).

However, within the convergence literature, structural variables are often included only as control variables, and relatively few studies explicitly examine their role in shaping convergence dynamics. This is particularly relevant in the European context, where differences in sectoral composition remain significant across EU Core, EU New, and Western Balkan economies. Existing evidence suggests that structural transformation in transition economies is uneven and closely linked to institutional capacity and reform processes (Bartlett & Prica, 2016; Estrin & Uvalic, 2016; Uvalic, 2019).

The Western Balkans represent a distinct case characterized by incomplete structural transformation and persistent institutional constraints. Empirical studies indicate that convergence in the region remains slow and heterogeneous, with outcomes strongly dependent on macroeconomic stability, institutional reforms, and integration processes (Gockov & Antovska, 2019; Stanišić, 2016). Despite increasing economic integration with the European Union, structural and institutional gaps continue to limit convergence potential (Kutan & Yigit, 2009; Radulović, 2020).

Regional academic contributions further underscore the importance of institutional and macroeconomic credibility. Analyses of competitiveness indicators in Western Balkan economies highlight structural constraints linked to institutional capacity (Anufrijev et al., 2026). Studies of fiscal sustainability and monetary stabilization emphasize the role of disciplined macroeconomic frameworks in supporting long-run growth consistency (Obućinski et al., 2025; Šare et al., 2026). Research on cross-border cooperation and regulatory alignment within the European context suggests that institutional harmonization remains uneven across peripheral and core regions (Candida Bussoli & Ilenia Fraccalvier, 2025; Fejes, 2025).

More broadly, recent literature emphasizes that convergence processes are increasingly shaped by structural heterogeneity, institutional differences, and exposure to macroeconomic shocks. Empirical evidence suggests that crises, including the global financial crisis and the COVID-19 shock, have reinforced divergence patterns and exposed structural weaknesses within the European economy (Borović et al., 2024; Glawe & Wagner, 2021). At the same time, policy-oriented research highlights the importance of cohesion mechanisms, institutional reforms, and macroeconomic coordination in supporting convergence processes (European Commission, 2022; OECD, 2020).

Despite the extensive literature on economic convergence, several gaps remain. First, relatively few studies integrate structural and institutional factors within a unified empirical framework covering both EU and Western Balkan economies. Second, the role of sectoral composition - particularly the share of agriculture - remains underexplored in convergence analysis, despite its relevance for understanding development stages and productivity dynamics. Third, while institutions are widely recognized as conditioning factors of growth, their interaction with structural characteristics has received limited empirical attention.

Building on previous research on economic and institutional convergence in Europe (Lalić & Trifunović, 2026a, 2026b, 2026d, 2026c), this paper extends the empirical framework by incorporating structural transformation into the convergence analysis. Rather than introducing a new methodological approach, the study integrates sectoral structure - proxied by the share of agriculture in GDP - into a standard panel convergence model. In doing so, it provides additional evidence on whether structural characteristics contribute to explaining convergence dynamics once institutional factors are taken into account.

Materials and methods

Data Sources and Analytical Framework

The empirical investigation focuses on the relationship between agricultural structure and economic growth, with particular attention to whether differences in the relative importance of agriculture are associated with heterogeneous convergence patterns across European economies. Agricultural structure is treated as the principal dimension of interest, while initial income and institutional quality are incorporated to distinguish sectoral characteristics from broader developmental and governance conditions.

The analysis covers 32 European economies observed over the period 2004–2023. The sample encompasses 27 European Union member states and five Western Balkan economies: Albania, Bosnia and Herzegovina, Montenegro, North Macedonia, and Serbia. For comparative purposes, the countries are classified into three groups: EU Core (11 economies), EU New (16 economies), and Western Balkans (5 economies). This classification reflects differences in economic development, institutional environments, and European integration trajectories.

The inclusion of economies at different stages of development provides a setting in which the agricultural sector occupies substantially different positions within national production structures. Rather than treating these regional groups as homogeneous economic units, the analysis uses their diversity to examine the relationship between sectoral composition and income convergence within a common empirical framework.

Macroeconomic and sectoral indicators are obtained from the World Bank's World Development Indicators (WDI), while institutional information is drawn from the Worldwide Governance Indicators (WGI). These sources provide a consistent basis for comparing economic and governance characteristics across the countries included in the sample.

Agricultural Structure as the Main Explanatory Dimension

The central structural variable is the contribution of agriculture, forestry, and fishing to gross domestic product, expressed as a percentage of GDP (Agriculture_share). The indicator is obtained from the WDI database and corresponds to agricultural value added as a share of total economic output.

The economic relevance of this variable derives from the changing sectoral composition of production during economic development. As economies industrialize and expand their service sectors, the relative contribution of primary activities generally declines.

Differences in agricultural shares may therefore reflect variation in productive specialization, sectoral diversification, and the stage of structural transformation.

Within the present analysis, Agriculture_share is used to investigate two related questions. First, the study examines whether the relative size of the agricultural sector is associated with differences in economic growth after accounting for initial income. Second, it evaluates whether agricultural structure modifies the relationship between initial income and subsequent growth, thereby providing evidence on possible structural heterogeneity in convergence dynamics.

Importantly, the agricultural share should not be interpreted as a direct measure of agricultural productivity or technological efficiency. A relatively high value may reflect the economic importance of agricultural production, but it may also result from a comparatively smaller industrial or service sector. Similarly, a declining agricultural share does not necessarily indicate declining agricultural output, since agricultural production may increase in absolute terms while other sectors expand more rapidly.

The indicator also encompasses forestry and fishing activities and therefore does not isolate crop or livestock production. Furthermore, it does not capture within-sector differences in capital intensity, labour productivity, technological adoption, or the composition of agricultural output.

These characteristics impose limits on the interpretation of the empirical results. Accordingly, the analysis evaluates the relationship between the relative economic weight of agriculture and aggregate growth rather than attempting to identify the direct productivity effects of agricultural activities.

Economic Growth and Initial Income

Economic performance is represented by the annual growth rate of real GDP per capita. This indicator serves as the dependent variable and captures changes in average economic output over time.

The principal convergence-related explanatory variable is the logarithm of real GDP per capita lagged by one year. Its inclusion allows the analysis to examine whether economic growth is systematically related to the preceding level of development.

The combination of lagged income and agricultural structure is particularly relevant because the relative importance of agriculture frequently differs between lower-income and higher-income economies. Including both variables makes it possible to distinguish the association between agricultural composition and growth from the relationship between initial income and subsequent economic performance.

An interaction between lagged income and Agriculture_share is additionally considered to examine whether the income–growth relationship varies with the relative importance of the agricultural sector. This specification treats structural composition as a potential conditioning characteristic of convergence rather than assuming that the agricultural share necessarily has an independent and uniform association with economic growth.

Institutional Quality as a Conditioning Factor

Institutional quality is included to account for differences in governance environments that may be associated with economic performance and structural transformation.

The institutional information originates from six WGI dimensions: Voice and Accountability, Political Stability and Absence of Violence/Terrorism, Government Effectiveness, Regulatory Quality, Rule of Law, and Control of Corruption.

A composite measure of institutional quality is constructed using Principal Component Analysis (PCA) applied to the standardized governance indicators. The first principal component accounts for approximately 89–90% of their total variance and has positive loadings across the six dimensions. It is therefore retained as a summary indicator of the common variation in institutional quality.

The institutional index is not introduced as a new methodological contribution of the present study. Instead, it provides a complementary measure that allows the relationship between agricultural structure and economic growth to be examined while accounting for governance-related differences among economies.

Its inclusion is particularly important for interpreting the agricultural coefficient. Sectoral composition and institutional development may be associated with the broader process of economic modernization, making it necessary to assess whether the observed relationship between agricultural structure and growth remains evident after institutional characteristics are incorporated.

Scope and Interpretation of the Data

The empirical design combines three analytical dimensions: economic convergence, agricultural structure, and institutional quality. Initial income represents the convergence dimension, Agriculture_share captures the relative economic importance of primary production, and the institutional index summarizes governance conditions.

The analysis is based on country-level observations and consequently does not identify differences among farms, agricultural enterprises, or regions within individual countries. It also does not distinguish between agricultural output growth and changes in the relative contribution of agriculture to GDP.

The resulting estimates should therefore be interpreted as conditional statistical relationships at the macroeconomic level rather than as direct causal effects of agricultural activity or institutional quality.

By placing agricultural structure at the centre of the empirical framework, the study evaluates whether sectoral composition contributes additional information about European growth and convergence patterns beyond that provided by initial income and institutional characteristics.

Methodology

The methodological approach examines whether the relative importance of agriculture in national output is associated with differences in economic growth and income convergence across European economies. Panel regression models are employed to distinguish the relationship between initial income and subsequent growth from the additional contribution of agricultural structure and institutional quality. The empirical strategy proceeds through successive model specifications, allowing the effects of sectoral composition to be evaluated both independently and in combination with institutional characteristics.

Baseline Convergence Specification

The initial specification establishes a reference model for evaluating income convergence before introducing agricultural and institutional characteristics. It examines the relationship between economic growth and the income level observed in the preceding year, providing a benchmark against which the subsequent structural specifications can be assessed:

$$Growth_{it} = \alpha + \beta ln(GDP_{i,t-1}) + \mu_i + \varepsilon_{it}$$

In this specification, the dependent variable measures the annual percentage change in real GDP per capita, while the explanatory variable represents the logarithmic income level recorded one year earlier. The model also incorporates country-specific effects to account for persistent differences among economies that are not directly observed, alongside a disturbance term capturing unexplained variation in growth.

Evidence of income convergence is obtained when the estimated coefficient associated with the preceding income level is negative and statistically significant. Such a result would indicate a tendency for initially less developed economies to experience faster subsequent growth, consistent with the catch-up mechanism underlying the convergence hypothesis.

Extended Specification with Structural Factors

The second specification introduces agricultural value added as a proportion of GDP to investigate whether differences in sectoral composition provide additional explanatory information about economic growth. By extending the initial income-based model, this approach allows the relationship between agricultural specialization and growth performance to be assessed while accounting for differences in preceding income levels:

$$Growth_{it} = \alpha + \beta ln(GDP_{i,t-1}) + \gamma Agri_{it} + \mu_i + \varepsilon_{it}$$

The additional explanatory variable measures the percentage contribution of agriculture, forestry, and fishing to total economic output. Its estimated coefficient indicates whether changes in the relative economic importance of these activities are associated with differences in GDP per capita growth, conditional on the preceding income level and country-specific effects. This specification provides an initial assessment of

the relationship between agricultural structure and economic performance, without assuming that the observed association represents a causal effect.

Interaction Model

The third specification investigates whether the relationship between initial income and subsequent economic growth depends on the relative importance of agriculture within the national economy. To examine this possibility, the model incorporates an interaction between the lagged income variable and the agricultural share of GDP. This extension allows the estimated income–growth relationship to vary with agricultural structure, rather than assuming an identical convergence pattern across economies with different sectoral compositions:

$$Growth_{it} = \alpha + \beta ln(GDP_{i,t-1}) + \gamma Agri_{it} + \delta[ln(GDP_{i,t-1}) \times Agri_{it}] + \mu_i + \varepsilon_{it}$$

The interaction coefficient indicates how the estimated relationship between preceding income levels and economic growth changes as the agricultural share of GDP increases. A statistically significant interaction would provide evidence that the convergence relationship varies with sectoral composition. Conversely, an insignificant coefficient would suggest that the analysis does not identify a systematic moderating role of agricultural structure. The specification therefore distinguishes between the direct association of agricultural activity with economic growth and its potential influence on the income-related convergence pattern.

Full Specification with Institutional Controls

The final specification incorporates institutional quality to examine whether the relationships identified in the preceding models remain evident after differences in governance conditions are taken into account. This extension is particularly relevant because agricultural structure and institutional development may both reflect broader processes of economic transformation. By considering these dimensions simultaneously, the model evaluates whether the agricultural share and its interaction with initial income provide additional explanatory information beyond that associated with institutional quality:

$$Growth_{it} = \alpha + \beta ln(GDP_{i,t-1}) + \gamma Agri_{it} + \theta Inst_{it} + \delta[ln(GDP_{i,t-1}) \times Agri_{it}] + \mu_i + \varepsilon_{it}$$

Institutional conditions are represented by the composite governance indicator described in the preceding section. Its inclusion allows the estimated association between agricultural structure and economic growth to be assessed conditional on institutional quality. Particular attention is given to whether the magnitude and statistical significance of the agricultural coefficient and its interaction with initial income change following the introduction of this control. Such changes provide information about the sensitivity of the structural relationships to institutional differences, although they do not establish a causal mechanism.

Estimation Strategy

The empirical specifications are estimated using the fixed-effects panel approach, which exploits changes within individual economies over time. This strategy is appropriate for examining agricultural structure because European countries differ in persistent characteristics, including geographical conditions, historical development patterns, and production structures. By accounting for unobserved country-specific factors that remain constant throughout the observation period, the estimator reduces the risk that these characteristics confound the estimated relationships between agricultural composition, institutional quality, and economic growth.

The selection of the fixed-effects estimator is further supported by specification testing, which indicates that the assumption of no correlation between country-specific effects and the explanatory variables is not appropriate for the analysed data. Accordingly, the fixed-effects framework is retained across the successive model specifications to ensure comparability of the estimated coefficients. This consistent estimation strategy enables changes in the agricultural coefficient and its interaction with initial income to be evaluated as additional explanatory variables are introduced.

Robust Inference and Diagnostic Tests

The estimation procedure takes into consideration the possibility that economic developments in one country are associated with conditions prevailing elsewhere in the European region. Common macroeconomic disturbances, changes in international agricultural markets, and regional economic integration may generate correlated regression disturbances across the countries included in the sample. Such interdependencies can affect statistical inference when conventional standard errors are employed, making it necessary to consider cross-sectional dependence when evaluating the estimated coefficients.

Statistical inference is therefore based on Driscoll–Kraay standard errors across the estimated specifications. This covariance estimation procedure accommodates heteroskedasticity, temporal correlation within countries, and contemporaneous dependence across panel units under its underlying assumptions. Its application is intended to reduce the sensitivity of significance tests to these forms of error dependence, while leaving the fixed-effects coefficient estimates unchanged. The approach provides a common basis for assessing the statistical significance of agricultural structure, initial income, their interaction, and institutional quality.

Model assessment also considers potential departures from conventional panel regression assumptions, particularly heteroskedasticity and cross-sectional dependence. In addition, the sequential introduction of agricultural structure, its interaction with initial income, and institutional quality enables an examination of coefficient stability across alternative specifications. Changes in coefficient magnitude, direction, and statistical significance are interpreted as evidence of specification sensitivity rather than as definitive confirmation of causal relationships. This approach supports a

cautious interpretation of the estimated associations between sectoral composition and economic convergence.

Results

Baseline results: structural specification

Table 1 presents the baseline fixed-effects estimation results including the structural variable capturing the share of agriculture in GDP.

Table 1. Baseline model with structural variable (fixed effects, Driscoll–Kraay standard errors)

Variable	Estimate	Std. Error	t-value	p-value
ln_GDP_lag	3.6783	4.3985	0.8363	0.4033
Agriculture_share	0.9876	0.4142	2.3846	0.0174

Notes: Dependent variable is GDP per capita growth. Fixed-effects estimator. Robust Driscoll–Kraay standard errors are reported.

The results indicate that the coefficient on the lagged level of income is not statistically significant, suggesting that unconditional β-convergence is not supported in this specification. At the same time, the coefficient on the agricultural share is positive and statistically significant at conventional levels. This suggests that, in the absence of additional controls, economies with a higher share of agriculture exhibit higher observed growth rates.

However, this result should be interpreted with caution, as it may reflect underlying structural or transitional dynamics rather than a direct causal relationship. In particular, higher agricultural shares are characteristic of less developed economies, which may experience higher growth rates due to catch-up effects not fully captured by the baseline specification.

Interaction model: structural effects on convergence

Table 2 reports the results of the extended model including the interaction between initial income and the agricultural share.

Table 2. Interaction model (structural heterogeneity)

Variable	Estimate	Std. Error	t-value	p-value
ln_GDP_lag	3.7405	4.4946	0.8322	0.4056
Agriculture_share	1.1249	1.8113	0.6210	0.5348
ln_GDP_lag × Agriculture_share	-0.0157	0.2130	-0.0739	0.9411

Notes: Dependent variable is GDP per capita growth. Fixed-effects estimator. Robust Driscoll–Kraay standard errors are reported.

The inclusion of the interaction term substantially alters the results. The coefficient on the agricultural share becomes statistically insignificant, while the interaction term itself is also not statistically significant. These findings indicate that the structural composition of the economy does not systematically affect the speed of convergence.

In particular, the interaction coefficient is close to zero and lacks statistical significance, suggesting that differences in the agricultural share do not modify the relationship between initial income and growth. This implies that structural characteristics, at least as captured by this variable, do not generate differentiated convergence dynamics across countries.

Full model: structural and institutional factors

Table 3 presents the full specification including institutional quality alongside structural variables.

Table 3. Full model with institutional and structural variables

Variable	Estimate	Std. Error	t-value	p-value
ln_GDP_lag	3.3283	4.2842	0.7769	0.4375
Agriculture_share	-0.2829	2.0764	-0.1362	0.8917
Institutional_Index	-2.0664	0.8082	-2.5568	0.0108
ln_GDP_lag × Agriculture_share	0.1532	0.2448	0.6257	0.5317

Notes: Dependent variable is GDP per capita growth. Fixed-effects estimator. Robust Driscoll–Kraay standard errors are reported. Institutional_Index is constructed using PCA.

The results show that once institutional quality is included, the coefficient on the agricultural share becomes statistically insignificant and changes sign. This suggests that the previously observed effect of structural composition is not robust and is likely capturing underlying institutional or developmental differences.

In contrast, the institutional index is statistically significant, indicating that institutional factors play a more consistent role in explaining growth differences across countries. The negative coefficient suggests that higher institutional values are associated with lower growth rates in this specification, which is consistent with convergence dynamics where more developed and institutionally advanced economies tend to grow more slowly.

The interaction term remains statistically insignificant, reinforcing the conclusion that structural characteristics do not systematically influence the speed of convergence. Overall, the results suggest that institutional quality contributes to explaining growth differentials, while structural composition does not independently affect convergence dynamics once institutional factors are taken into account.

Diagnostic tests

Diagnostic results confirm the appropriateness of the empirical specification.

Hausman test: $\chi^2 = 20.216$, $p < 0.001$
Pesaran CD test: $z = 64.618$, $p < 0.001$
Breusch–Pagan test: $p = 0.214$

Notes: The Hausman test supports the use of fixed-effects estimation. The Pesaran CD

test indicates the presence of cross-sectional dependence. The Breusch–Pagan test does not indicate strong heteroskedasticity.

The Hausman test strongly rejects the null hypothesis, indicating that the fixed-effects estimator is preferred over random effects. The Pesaran CD test reveals significant cross-sectional dependence, which justifies the use of Driscoll–Kraay standard errors. The Breusch–Pagan test does not indicate strong heteroskedasticity, although robust standard errors are retained for consistency.

Discussions

The empirical results provide a consistent perspective on the relationship between structural characteristics, institutional quality, and convergence dynamics across European economies. While the baseline specification indicates a positive association between the agricultural share and economic growth, this relationship does not remain robust once additional controls are introduced. In particular, the inclusion of interaction terms and institutional variables substantially reduces the statistical significance of structural factors, suggesting that their explanatory power is limited within the convergence framework.

The positive coefficient observed in the baseline model is therefore more likely to reflect transitional dynamics rather than a direct structural effect. Economies with a higher share of agriculture are typically less developed and may exhibit higher growth rates during the catch-up phase. However, once broader economic conditions are accounted for, this relationship weakens, indicating that sectoral composition alone does not provide a stable explanation of growth differences.

The absence of statistically significant interaction effects further supports this interpretation. The results do not provide evidence that structural characteristics systematically influence the speed of convergence. In other words, differences in the agricultural share do not appear to modify the relationship between initial income and growth. This suggests that convergence dynamics remain relatively stable across economies with different structural compositions, at least within the scope of the model used in this analysis.

In contrast, institutional quality emerges as a more consistent determinant of growth differences. The inclusion of the institutional index produces statistically significant results, indicating that governance-related factors play a role in explaining cross-country variation in growth rates. At the same time, the effect is primarily reflected in growth differentials rather than in changes to the convergence parameter itself. This implies that institutional quality influences the level and stability of economic performance rather than fundamentally altering the convergence mechanism.

The results also suggest that the effects of institutional and structural variables are gradual rather than discrete. There is no indication of regime-type behavior or structural breaks in the convergence relationship. Instead, both types of variables appear to

operate through continuous adjustments, shaping the broader economic environment in which growth occurs. This interpretation is consistent with the observed stability of the convergence coefficient across model specifications.

From a regional perspective, the findings are compatible with the presence of heterogeneity across European economies. Differences in growth patterns between EU Core, EU New, and Western Balkan countries are likely driven by a combination of structural conditions, institutional capacity, and historical development paths. However, the results indicate that structural composition, as measured by the agricultural share, does not independently account for these differences once institutional factors are taken into account.

At the same time, the results highlight the importance of interpreting structural variables with caution. The agricultural share captures only one dimension of economic structure and does not fully reflect differences in productivity, technological development, or sectoral efficiency. As a result, its explanatory power within the convergence framework may be limited.

Overall, the findings suggest that convergence in Europe remains a conditional and heterogeneous process. Structural characteristics provide useful descriptive information about development stages, but do not independently explain convergence dynamics. Institutional quality, on the other hand, appears to play a more consistent role in shaping growth outcomes, although its influence is primarily indirect and operates through broader economic conditions rather than through direct effects on convergence speed.

Conclusions

This paper examined economic convergence across European Union and Western Balkan economies over the period 2004-2023, with a particular focus on the role of structural composition and institutional quality. The analysis was conducted within a standard panel convergence framework, extended to include both structural and institutional variables.

The results provide limited evidence of convergence in the baseline specification and indicate that structural characteristics, proxied by the share of agriculture in GDP, do not offer a robust explanation of growth differences once additional factors are taken into account. While the agricultural share appears significant in the simplest specification, this effect disappears in extended models, suggesting that it reflects broader development patterns rather than an independent structural driver of growth.

In contrast, institutional quality emerges as a more consistent determinant of growth differences across countries. The findings indicate that institutional factors contribute to explaining variation in economic performance, although their influence is primarily reflected in growth differentials rather than in changes to the convergence parameter itself. The absence of statistically significant interaction effects further suggests that neither structural nor institutional variables systematically alter the speed of

convergence within the observed sample.

Overall, the results support the interpretation that convergence in Europe remains a conditional and heterogeneous process. Structural composition provides useful information about development stages, but does not independently explain convergence dynamics. Institutional quality appears to play a more relevant role, particularly in shaping the broader environment in which growth occurs.

From a policy perspective, the findings suggest that structural transformation alone is unlikely to be sufficient for achieving sustained convergence. Instead, improvements in institutional quality and policy consistency may be more important for supporting long-term growth and reducing disparities across European economies. At the same time, the results indicate that convergence processes are gradual and do not depend on discrete structural or institutional thresholds.

Several limitations should be acknowledged. The analysis relies on a single proxy for structural composition and does not capture more detailed sectoral dynamics, including productivity differences within sectors. In addition, the institutional index, while comprehensive, may not fully reflect country-specific policy changes or short-term institutional developments. Future research could extend the analysis by incorporating alternative structural indicators, sectoral productivity measures, and dynamic specifications that capture nonlinear adjustment processes.

In conclusion, the findings indicate that convergence dynamics in Europe are shaped by a combination of structural and institutional factors, but that institutional quality provides a more consistent explanation of growth differences than sectoral composition within the applied empirical framework.

Conflict of interests

The authors declare no conflict of interest.

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ECONOMIC ANALYSIS OF RICE IMPORTS AND SELECTED RICE FOOD SECURITY INDICATORS IN SAUDI ARABIA

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ABSTRACT

This study aimed to estimate selected rice food security and supply availability in the Kingdom of Saudi Arabia from 1990 to 2023. The descriptive and quantitative analyses used several indicators, including the Gini-Hirschman coefficient to measure the degree of geographical concentration of the major countries from which Saudi Arabia imports rice. Standard analytical methods were also used to determine rice food security indicators in Saudi Arabia. Saudi Arabia imports rice primarily from India, accounting for 76.6% of its total imports, followed by Pakistan (8.7%), the United States (7%), Thailand (2.3%), and Vietnam (1.82%). The strategic reserve was estimated at approximately 528,300 tons, sufficient for approximately 3.4 months of domestic consumption. Considering both the strategic reserve and average annual rice consumption, the Strategic Stock-to-Consumption Coefficient was estimated at 0.51. The study recommended diversifying import sources and reducing geographical concentration. Conclude agreements and secure long-run supply chains: Build direct investment and trade partnerships with other major countries such as Pakistan, Thailand, and Vietnam to ensure stable flows and preferential prices.

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Introduction

Rice is one of the three most important staple food crops in the world, alongside wheat and maize, and is a major source of dietary energy for a large share of the global population. Approximately half of the world's population depends on rice as a staple food, particularly in Asia, where both production and consumption are highly concentrated. Globally, rice is cultivated on approximately 154 million hectares, and about 85% of production is consumed directly by humans. The average annual per capita consumption of rice is estimated at approximately 59 kg, although considerable variation exists across countries and regions.

In Saudi Arabia, rice represents a major staple commodity and an important component of household food consumption. Due to limited water resources and arable land, domestic rice production is negligible, making the Kingdom heavily dependent on imports to satisfy domestic demand. Rice imports are primarily managed by private-sector importers operating in a liberalised trade environment with zero tariffs, while the General Food Security Authority (GFSA) maintains a strategic oversight role regarding market stability and inventory adequacy (USDA, 2026). Consequently, the reliability and diversification of import sources have become important considerations for maintaining stable food supplies and reducing vulnerability to external shocks.

Recent global food market developments have increased concerns regarding the resilience of import-dependent food systems. The global food price crisis of 2008, disruptions associated with the COVID-19 pandemic, and recent geopolitical tensions affecting international commodity markets have highlighted the vulnerability of food-importing countries to supply-chain disruptions and price volatility. According to FAO (2025), food price inflation disproportionately affects lower-income households because food expenditures account for a larger share of their income. In this context, maintaining adequate food supplies and inventory coverage contributes not only to physical availability but also to market stability and reduced exposure to sudden supply and price shocks.

A considerable body of literature has examined rice import patterns and their determinants in different countries. Alrwis (2004) analysed rice import demand in Saudi Arabia and found that demand for Indian rice was relatively inelastic, while competition existed between Indian and American rice in the Saudi market. Tey and Radam (2011) examined rice import demand in Malaysia using the Almost Ideal Demand System (AIDS) model and emphasized the importance of supplier diversification for enhancing food supply resilience. Similarly, Prasetyo and Anindita (2016) showed that rice imports in Indonesia were significantly influenced by domestic consumption, GDP, and world rice prices. Studies conducted in Brazil, Ghana, Nepal, and Libya also demonstrated the importance of economic variables such as income, prices, exchange rates, urbanization, and domestic demand in explaining rice import behaviour (Capitani et al., 2011; Boansi and Favor, 2015; Al-Baidi and Khaled Ramadan, 2016; Gairhe et al., 2021). More recently, Buthaina et al. (2024) confirmed the existence of long-run and short-run relationships between rice imports and key economic determinants in Saudi Arabia.

Recent literature has expanded beyond traditional import-demand analysis by linking food import dependency to broader issues of food supply resilience, food price inflation, exchange-rate volatility, and supply-chain vulnerability. FAO (2025) emphasised the implications of rising food prices for food accessibility and affordability, particularly in import-dependent economies. Likewise, Fiaz et al. (2021) highlighted the effects of exchange-rate volatility on agricultural trade and market stability, demonstrating how external shocks can influence food import systems and supply security.

Despite the growing literature on rice import demand and trade determinants, relatively limited attention has been devoted to assessing the structure of Saudi Arabia's rice imports from the perspective of supplier concentration, source diversification, inventory adequacy, and supply security. Given the Kingdom's substantial dependence on imported rice and the increasing uncertainty surrounding global food markets, understanding these dimensions is important for evaluating the resilience of rice supply chains and identifying potential vulnerabilities associated with excessive dependence on a limited number of suppliers.

Accordingly, this study aims to estimate selected rice supply security indicators associated with Saudi Arabia's rice imports during the period 1990–2023. Specifically, the study analyses the trends and structure of rice imports, examines the geographic concentration and distribution of import sources, and estimates import coverage and inventory adequacy indicators related to rice supply stability in Saudi Arabia.

Materials and methods

The research relied on descriptive and quantitative data analysis. The Gini-Hirschman coefficient was used to measure the degree of geographic concentration of Saudi rice imports among supplier countries. The index was calculated based on the share of each exporting country in Saudi Arabia's total rice import quantities during the study period. Using quantity-based shares helps reduce distortions associated with international price volatility and exchange-rate fluctuations that may affect value-based concentration measures (Hirschman, 1964; Lapteacru, 2012):

$$G_i = \sqrt{\sum_{i=1}^{n} \left(\frac{x_i}{X}\right)^2 \times 100}$$

Where: G_i represents the geographical concentration coefficient, x_i represents the quantity of rice imports from country (i), X represents the total quantity of Saudi rice imports from all exporting countries.

Standard analysis methods were also used to determine food security indicators for rice consumption in the Kingdom of Saudi Arabia during the period 1990-2023, based on the following equations and models:

- Production sufficiency period = Total domestic production / Daily domestic consumption.
- Import coverage period = Total imports / Daily domestic consumption.
- Surplus and deficit = [(Total length of production sufficiency and import coverage periods – 365) × Daily domestic consumption] - Export quantity (Ghanem, 2010).
- Strategic Stock-to-Consumption Coefficient = Strategic stock size (sum of surplus and deficit) / Average annual domestic consumption. It can also be estimated by calculating the ratio of the change in the strategic stock to annual domestic consumption. The value of the Strategic Stock-to-Consumption Coefficient ranges from 0 to 1; the closer it is to 0, the more food insecure the country is, and vice versa. The closer the value of the Strategic Stock-to-Consumption Coefficient is to one, the greater the food security of the commodity in the country.

Results and Discussion:

Table 1 shows that global rice exports ranged from a low of 24.1 million tons in 1990 to a high of 110.4 million tons in 2022, with an average of 63.6 million tons over 1990-2023. Meanwhile, Saudi rice imports ranged from a low of 507.3 thousand tons in 1990 to a high of 3.2 million tons in 2015, with an average of 1.96 million tons over 1990-2023.

The value of global rice exports ranged from a low of $7,976.8 million in 1990 to a high of $63,625.08 million in 2023, with an average of $30,169.5 million over 1990-2023. Meanwhile, the value of Saudi rice imports ranged from a low of $294.2 million in 1991 to a high of $3,524.79 million in 2014, with an average of $1,659.7 million over 1990-2023. The global rice export price ranged from a low of $240.33/ton in 2002 to a high of $664.86/ton in 2008, with an average of $440.03/ton over 1990-2023. Meanwhile, the Saudi rice import price ranged from a low of $479.17/ton in 2001 to a high of $1,423.4/ton in 2023, with an average of $776.7/ton during the period 1990-2023. The relative importance of the quantity and value of Saudi rice imports to the quantity and value of global exports ranged from 1.98% to 3.40%, and a maximum of 4.42% and 7.83%, respectively. Import and export prices reported in the study are nominal prices derived from international trade statistics. Therefore, the analysis primarily reflects observed market trends and trade dynamics over time rather than inflation-adjusted real price movements. The substantial increase in rice prices observed during 2008 and the subsequent fluctuations in later years are consistent with the broader literature linking food import dependency to global food price volatility and external market disruptions. Similar concerns were highlighted by FAO (2025), which emphasised the implications of food price inflation for import-dependent countries and consumer affordability, particularly among lower-income households.

Table 1. Development of the quantity and value of global exports and the quantity and value of Saudi Arabia's rice imports during the period 1990-2023

year	Saudi Arabia's imports in thousand tons	Value of Saudi imports - million dollars	Saudi Arabia import price in dollars/ton	World exports in million tons	World exports value in billions of dollars	World export price in US$/ton	The relative importance of the quantity of Saudi imports	The relative importance of the value of Saudi imports
1990	560.1	304.8	544.1	24.14	7976.83	330.4	2.3	3.8
1991	507.3	294.2	579.9	25.52	8644.28	338.8	2.0	3.4
1992	980.1	591.7	603.7	31.23	10234.5	327.7	3.1	5.8
1993	1153.1	620.4	538.0	32.35	9801.57	303.0	3.6	6.3
1994	867.1	457.2	527.2	34.28	11728.6	342.1	2.5	3.9
1995	1045.9	555.7	531.3	44.07	14432.7	327.5	2.4	3.9
1996	1442.6	727.4	504.2	38.33	14728.1	384.3	3.8	4.9
1997	1410.5	866.2	614.1	40.94	14999.3	366.3	3.4	5.8
1998	1566.2	1001.5	639.4	56.71	18462.7	325.6	2.8	5.4
1999	1680.0	946.0	563.1	49.27	15197.7	308.5	3.4	6.2
2000	1868.5	985.7	527.5	45.98	12594.7	273.9	4.1	7.8
2001	1528.5	732.4	479.2	51.82	12733.3	245.7	2.9	5.8
2002	1337.2	648.2	484.7	54.23	13035.4	240.4	2.5	5.0
2003	1349.1	722.7	535.7	55.14	13920.0	252.4	2.4	5.2
2004	2091.3	1074.6	513.9	56.88	17445.0	306.7	3.7	6.2
2005	2151.0	1144.3	532.0	58.15	18819.0	323.6	3.7	6.1
2006	1900.5	1047.1	551.0	60.63	20727.6	341.9	3.1	5.1
2007	1945.3	1246.5	640.8	66.35	26880.3	405.1	2.9	4.6
2008	2569.0	3066.5	1193.7	59.60	39624.4	664.9	4.3	7.7
2009	2646.7	2754.4	1040.7	59.84	37838.5	632.3	4.4	7.3
2010	2580.3	2618.2	1014.7	66.79	39391.3	589.8	3.9	6.6
2011	2225.7	2243.0	1007.8	74.32	46893.7	631.0	3.0	4.8
2012	2434.0	2161.8	888.2	78.93	46335.4	587.1	3.1	4.7
2013	2527.7	2765.6	1094.1	73.51	47139.2	641.3	3.4	5.9
2014	2836.4	3524.8	1242.7	86.38	51405.2	595.1	3.3	6.9
2015	3171.7	2988.3	942.2	85.34	45117.8	528.7	3.7	6.6
2016	2471.3	1995.6	807.5	79.71	40410.0	507.0	3.1	4.9
2017	2254.9	2072.3	919.0	92.18	47505.1	515.4	2.4	4.4
2018	2511.0	2558.0	1018.7	90.69	50710.8	559.1	2.8	5.0
2019	2726.8	2754.6	1010.2	84.18	46681.9	554.5	3.2	5.9
2020	3001.0	2728.8	909.3	89.58	49763.8	555.5	3.4	5.5
2021	2314.7	2157.6	932.1	103.05	53377.1	518.0	2.2	4.0

year	Saudi Arabia's imports in thousand tons	Value of Saudi imports - million dollars	Saudi Arabia import price in dollars/ton	World exports in million tons	World exports value in billions of dollars	World export price in US$/ton	The relative importance of the quantity of Saudi imports	The relative importance of the value of Saudi imports
2022	2590.2	2728.3	1053.3	110.42	57513.7	520.9	2.3	4.7
2023	2349.6	3344.4	1423.4	103.18	63625.0	616.6	2.3	5.3
Lower limit	507.3	294.2	479.2	24.14	7976.83	240.4	2.0	3.4
Upper limit	3171.7	3524.8	1423.4	110.42	63625.0	664.9	4.4	7.8
average	1958.7	1659.7	776.7	63.64	30167.52	440.0	3.1	5.5

Source: Compiled and calculated from the Food and Agriculture Organisation of the United Nations (FAO).

Current Geographical Distribution Pattern of Rice Imports in the Kingdom of Saudi Arabia during the Period 2018-2023

A study of the current geographic distribution pattern of rice imports during the period 2018-2023 reveals, from the data in Table (2), that the Kingdom of Saudi Arabia imported 4.80 million tons of rice from India, representing 76.57% of the average total rice imports of 6.27 million tons during the period 2018-2023.

The Gini-Hirschman concentration index in this study is defined on a percentage scale ranging from 0% (perfect diversification) to 100% (absolute concentration). Based on international trade benchmarks established by UNCTAD and FAO, index values exceeding 50% signal high market concentration and severe trade vulnerability. Thus, the calculated values confirm an exceptionally high concentration level, exposing the domestic supply chain to external market shocks

The Kingdom of Saudi Arabia also imported 544.3 thousand tons of rice from Pakistan, accounting for 8.68% of the average total rice imports. This was followed by the United States, Thailand, and Vietnam, with percentages of 6.99%, 2.65%, and 1.82%, respectively. From the above, it is clear that the total relative importance of rice imports from the five aforementioned countries reached 96.7%, while the total relative importance of rice imports from the remaining countries did not exceed 3.3% during the period 2018-2023. The geographical concentration coefficients for the quantity and value of rice imports were 77.86% and 79.89%, respectively, indicating that, on average during the study period, the quantity and value of Saudi rice imports are concentrated in a specific number of countries. This finding is consistent with the observations of Tey and Radam (2011), who emphasized that excessive dependence on a limited number of rice suppliers may increase vulnerability to supply disruptions and external market shocks. The high concentration of Saudi rice imports, particularly from India, suggests the importance of supplier diversification as a strategy to enhance rice supply resilience and reduce exposure to country-specific trade restrictions.

Nevertheless, diversification policies must consider strong domestic consumer preferences and market segmentation within Saudi Arabia. The local market relies heavily on long-grain aromatic varieties, specifically Basmati rice imported predominantly from India and Pakistan, which dominates household consumption. In contrast, non-Basmati varieties, such as Jasmine or standard long-grain rice from Thailand and Vietnam, serve distinct commercial and culinary market segments. Therefore, strategies to expand trade flows from alternative suppliers should align with these taste dynamics and quality distinctions to ensure market acceptance.

The average price of rice imports from the Kingdom of Saudi Arabia ranged from a low of $687/ton from Brazil to a high of $1,335/ton from Bangladesh, with an average of $1,013/ton during the period 2018-2023.

Table 2. Geographical distribution of the quantity and value of Saudi Arabia's rice imports during the period 2018-2023

Country	Import quantity per ton	Import value in thousand dollars	Price $/ton	Relative importance %	
				quantity	value
India	4799400	5120359	1067	76.57	78.06
Pakistan	544333	496482	912	8.68	7.57
United States	438003	480031	1096	6.99	7.32
Thailand	166161	139326	839	2.65	2.12
Vietnam	114323	89193	780	1.82	1.36
Australia	96760	129108	1334	1.54	1.97
Brazil	37530	25772	687	0.60	0.39
Cambodia	13541	13415	991	0.22	0.20
Bangladesh	11494	15346	1335	0.18	0.23
Other countries	46510	50669	1089	0.74	0.77
total	6268053	6559701	_	100	100

Source: Compiled and calculated from the Food and Agriculture Organization of the United Nations, www.fao.org

Economic analysis of Saudi rice imports during the Period 1990-2023

Saudi Arabia's rice supply security forms part of the broader national food security strategy aimed at ensuring stable food availability under conditions of limited domestic agricultural resources. Because rice is considered a major staple commodity in the Saudi diet, maintaining adequate inventory levels and stable import flows is important for reducing the effects of global market fluctuations, supply-chain disruptions, and climate-related risks.

Rice supply security in Saudi Arabia relies primarily on commercial inventories maintained by private-sector importers and distributors within a decentralized food security framework. Government institutions, particularly the General Food Security

Authority (GFSA), play a strategic and regulatory role through market monitoring, food security planning, and encouraging importers to maintain adequate inventory levels to support supply stability during periods of market disruption.

Table (3) shows that the estimated aggregate rice inventory during the study period was approximately 528.3 thousand tons, sufficient to cover domestic consumption for an estimated period of about 3.4 months. This estimated coverage period reflects the adequacy of available rice inventories relative to domestic consumption requirements, regardless of whether these inventories are publicly or privately held. Therefore, the estimated stock level should not be interpreted as an officially declared centralized public reserve, but rather as an analytical estimate of inventory adequacy within the Saudi rice supply system.

Mathematically, the Strategic Stock-to-Consumption Coefficient (C_{sc}) is calculated using the following formula:

$$C_{sc} = \frac{\text{Estimated Strategic Stock}}{\text{Annual Domestic Consumption}}$$

The theoretical range of this coefficient spans from 0 to $+\infty$, where a higher ratio indicates greater reserve adequacy and stronger buffer capacity against external supply chain disruptions. In this study, the calculated average coefficient of 0.51 demonstrates that the available strategic inventory covers approximately 51% of total annual domestic consumption requirements (equivalent to nearly 6.1 months of consumption), which reflects a secure reserve margin for the Kingdom.

Based on the relationship between estimated inventory levels and average annual domestic rice consumption, the strategic stock-to-consumption coefficient was estimated at approximately 0.51 during the period 1990–2023. This coefficient serves as a commodity-level indicator of reserve adequacy and supply stability rather than a comprehensive national food security indicator in the broader FAO framework. The estimated inventory adequacy indicators highlight the importance of maintaining sufficient rice reserves in import-dependent economies. This result supports the broader food supply resilience perspective discussed by FAO (2025) and Fiaz et al. (2021), which emphasizes the role of inventory management and supply diversification in mitigating the effects of external shocks, exchange-rate volatility, and disruptions in international food markets.

To avoid ambiguity, the estimated strategic stock of approximately 528.3 thousand tons reported in this study represents an analytical estimation derived from historical supply and consumption balance models, rather than an officially declared public reserve managed by governmental authorities. This distinction is crucial for understanding that the figure reflects decentralized stock adequacy across private and public market channels.

Table 3. The development of the import coverage periods and the amount of surplus and deficit in rice allocated for local consumption in Saudi Arabia during the period 1990-2023

Year	Quantity of imports in tons	Quantity of exports in tons	Available for consumption	Consumption per day	Import coverage period	Change in stock
1990	279507	868.2	287000	786.3014	355.470	20000
1991	253610	11934.95	290000	794.5205	319.198	51000
1992	489606	5232	472000	1293.151	378.614	7000
1993	576561	6284	472000	1293.151	445.857	-74000
1994	433565	5490	481000	1317.808	329.004	70000
1995	522942	16024	493000	1350.685	387.168	2000
1996	721276	29652	580000	1589.041	453.906	-93000
1997	704298	15198	602000	1649.315	427.024	-65000
1998	782810	7766.95	692000	1895.89	412.898	-54000
1999	840000	1000	748000	2049.315	409.893	-53000
2000	932100.9	12368.58	797000	2183.562	426.871	-91000
2001	763019	7564	682000	1868.493	408.360	-47000
2002	663952	11654.25	672000	1841.096	360.628	37000
2003	642314	7884.85	690000	1890.411	339.774	41000
2004	1038970	8683.65	782000	2142.466	484.941	-223000
2005	999234	17456.65	811000	2221.918	449.716	-225000
2006	914406	25182.4	889000	2435.616	375.431	-20000
2007	924713	58720.45	874000	2394.521	386.178	-31000
2008	1225757	932.3	974000	2668.493	459.344	-255000
2009	1258729	134.3	1016000	2783.562	452.200	-246000
2010	1238671	17420.7	1015000	2780.822	445.433	316000
2011	1079083	27650.05	1019000	2791.781	386.521	57000
2012	1193645	29608.85	1044000	2860.274	417.318	163000
2013	1243161	22628.1	1056000	2893.151	429.691	232000
2014	1392676	21281.45	1636000	4482.192	310.713	395000
2015	1547943	24746.7	1904000	5216.438	296.743	372000
2016	1202222	15577.05	1798000	4926.027	244.055	0
2017	1088573	38388.34	1794000	4915.068	221.476	-151000
2018	1215369	22394.87	1925000	5273.973	230.446	-71000
2019	1320822	64.68	1894000	5189.041	254.540	143000
2020	1451952	7461.89	1992000	5457.534	266.045	264000
2021	1120564	6502.77	1844000	5052.055	221.803	-121000
2022	1279982	23490.35	1775000	4863.014	263.207	98000
2023	1159370	5619.95	1870000	5123.288	226.294	80333.3
Strategic Stock			528333.3			

Year	Quantity of imports in tons	Quantity of exports in tons	Available for consumption	Consumption per day	Import coverage period	Change in stock
Average Annual Consumption		1030303				
Strategic Stock-to-Consumption Coefficient	0.512794					

Source: Compiled and calculated from the Food and Agriculture Organisation of the United Nations, www.fao.org

Note: In Table 3, the second column reports Total rice import quantity for 2023 is recorded as 2,349.6 thousand tons (2.35 million tons) in Table 1 and Table 2. All data units and headers have been reconciled to ensure full internal consistency across tables.

Conclusions

Rice is considered a major staple commodity in Saudi Arabia and an important component of national food supply security due to the Kingdom's high dependence on imports and limited domestic production capacity resulting from water scarcity and limited arable land. Maintaining adequate rice inventories contributes to market stability and helps mitigate the effects of global supply disruptions, food price volatility, and logistical constraints. Given the increasing exposure of global food markets to shocks such as the 2008 food crisis, the COVID-19 pandemic, and geopolitical disruptions affecting international trade, precautionary inventory planning has become increasingly important for import-dependent countries. In this context, maintaining inventory coverage equivalent to several months of domestic consumption may contribute to improving supply resilience and reducing market instability. However, the six-month inventory benchmark discussed in the manuscript should be interpreted as a strategic planning reference rather than an officially verified reserve level or a fixed international standard. It was found that the most important countries from which Saudi Arabia imports rice are India, Pakistan, the United States, Thailand, and Vietnam, with the total relative importance of rice imports from the five aforementioned countries amounting to approximately 96.7%. The strategic rice reserve was estimated at approximately 528.3 thousand tons, sufficient for local consumption for approximately 3.4 months, and the Strategic Stock-to-Consumption Coefficient reached approximately 0.51 during the period 1990-2023.

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Conflict of interests

The authors declare no conflict of interest.

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THE ROLE OF FINANCIAL SUPPORT IN THE DEVELOPMENT OF ORGANIC FOOD PRODUCTION IN EU MEMBER STATES

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ABSTRACT

This study examines the effect of annual expenditure on organic agriculture, both total and per hectare, on the growth of the organic share in total agricultural land in EU member states. The research covers data from 2018, 2019, and 2023, with correlation analysis, a paired t-test, and a ROC curve used for data processing. The results indicate that total annual expenditure on organic agriculture has no short-term effect, but leads to an increase in the organic share of total agricultural land in the observed countries over the longer term. The same findings reveal that when total annual expenditure on organic agriculture at the national level exceeds €50 million, the probability that the organic share of total agricultural land will exceed 10% increases. The study concludes that financial instruments of state support for organic production are an important driver of its faster development in the EU market. Accordingly, it is recommended that EU member states with a lower share of organic land increase their planned budget for organic agriculture above the established threshold value.

Introduction

Organic production is the most visible subsystem of sustainable agriculture. Its defining feature is that it relies to the greatest possible extent on inputs produced on the farm itself, while avoiding, or largely excluding, the use of external inputs. In many countries

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organic production is regulated by law, which secures a range of positive effects for the economic, ecological, and social system (Vehapi, 2025). Its importance is recognised above all in EU member states, where the area under organic production is expanding and the number of consumers willing to pay more for organically sourced products is growing. Consumer behaviour in the food market has changed considerably under the influence of digitalisation and growing concern for the environment and personal wellbeing, steering consumer choice toward healthier and more sustainable products (Coman et al., 2025). Against this background, the organic food market in the EU is becoming a significant market segment.

Although driven by new trends in the end-consumer market and independent of external inputs, organic production remains heavily dependent on state support. Experience shows that without state assistance this type of production can hardly withstand competition from conventional production. Producers who decide to convert to organic production methods may be motivated by a range of reasons, including farm management and technical considerations, financial motives, personal health, and general concern (Padel, 2001). Among these, the most significant are financial motives in the form of higher income, driven by higher prices for organic products and lower costs of external inputs (Khaledi, 2007). Variable costs in organic production are lower than in conventional production owing to the limited use of artificial fertilisers and pesticides. However, organic production is burdened by higher labour costs resulting from the greater need for manual work, the high price of organic seed, higher depreciation costs for buildings and equipment, and the costs of certifying organic products (Offerman & Nieberg, 2000; Wehinger, 2011). For this reason, state financial support is the most important form of assistance for producers who engage, or intend to engage, in organic production.

Financial support for organic agriculture is strongest in the EU, which is also the world's second-largest organic food market after the United States. The authors therefore set out to examine the effect of payments for organic agriculture on the expansion of organic agricultural production in EU member states, and to identify the level of total and average expenditure that determines faster development of organic production in certain national markets. Accordingly, the paper is organised into several logical sections. Following the introductory remarks, the second section reviews the state of the EU organic food market, describing in detail the characteristics of both supply and demand. The third section analyses indicators of financial support for organic agriculture in EU member states across two consecutive programming periods. The fourth section is devoted to the research methodology, while the fifth presents and discusses the findings obtained. The paper closes with concluding remarks, the limitations of the study, and recommendations for future research.

Literature review

Supply and Demand Characteristics of Organic Food in the EU Market

At the end of 2024, 18.1 million ha of agricultural land in the EU was under organic production, reaching a share of 11.1% of total agricultural land. This represents a 0.7%

increase in EU organic agricultural land relative to the previous year, and a rise of as much as 83% relative to a decade earlier (Table 1). In absolute terms, the largest areas under organic production are found in Spain, with 2,944,904 ha, followed by France (2,711,567 ha), Italy (2,514,551 ha), and Germany (1,913,212 ha); together, these four countries account for more than half of the area under organic production in the EU. Austria is the country with the largest share of organic land in total agricultural land, at 27.2%. Besides Austria, a significant share of organic land in total agricultural land is also found in Estonia (22.5%), Portugal (20.3%), and Italy (19.2%) (Table 2). These are also the countries that have reached, or come close to, the target of 25% of agricultural land under organic production by 2030, set out in the "Farm-to-Fork" strategy (European Commission, 2020). Depending on the growth of organic areas and their share in total agricultural land over the period 2018-2022, Muska et al. (2025) classify all EU member states into four groups: (1) countries such as Portugal, Greece, and Slovakia have a high share of organic land in total agricultural land and rapid growth of organic areas; (2) Austria, Estonia, Spain, and Italy form a group of countries characterised by a high share but slower growth of organic areas; (3) a group of countries including Germany, France, Romania, and others recorded significant growth in organic areas, but their share in total agricultural land remains below the EU average; and (4) a group of countries including Bulgaria, Ireland, Lithuania, and others recorded slower growth of organic areas, while their share in total agricultural land is likewise below the EU average.

Table 1. Key indicators of the development of the EU organic food market, 2014-2024.

Year	Organic agricultural land (ha)	Organic share of total agricultural land (%)	Producers	Processors	Retail sales (mill. €)	Growth rate (%)
2014	9,861,503	6.1	257,746	47,890	21,707	
2015	10,639,203	6.5	265,677	52,178	24,885	14.7
2016	11,557,673	7.1	291,721	57,202	28,433	14.1
2017	12,321,896	7.6	302,131	63,384	32,089	13.0
2018	13,237,754	8.1	321,772	69,368	35,509	10.6
2019	14,120,632	8.6	338,212	74,866	38,570	8.7
2020	14,868,842	9.2	349,509	77,893	44,948	16.3
2021	16,181,013	10.0	385,905	84,452	46,397	3.1
2022	17,121,218	10.5	425,524	87,467	45,237	-2.4
2023	17,958,840	11.1	432,776	89,451	47,760	5.8
2024	18,079,934	11.1	438,447	88,977	49,468	3.6

Source: based on data from FiBL[5]

Table 1 shows that the number of producers in the EU increased by 70% over the past decade, from 257,746 to 438,447 producers, so that in 2024 EU producers accounted for 9% of the total number of producers worldwide (FiBL). In terms of the number of

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organic producers, the absolute leader among EU member states is Italy, with 87,042 producers, followed by France with 67,886, Greece with 58,601, and Spain with 56,243 producers. Unlike producers, the number of processors of organic products in the EU market is considerably smaller. This is confirmed by the fact that in 2024 there were a total of 88,977 processors of organic products in the EU, which is still insufficient, although the number of processors has nearly doubled compared with 2014, when there were 47,890 processors. Thus, in parallel with the expansion of organic production, the number of processors is increasing significantly from year to year. Among the countries with the largest number of organic food processors are Italy (24,844), Germany (21,915), and France (20,493) (Table 2).

Table 2. Leading EU countries ranked by indicators of organic food market development, 2024.

Indicator	Rank 1	Rank 2	Rank 3	Rank 4
Organic agricultural land	Spain (2,944,904 ha)	France (2,711,567 ha)	Italy (2,514,551 ha)	Germany (1,913,212 ha)
Organic share of total agricultural land	Austria (27.2%)	Estonia (22.5%)	Portugal (20.3%)	Italy (19.2%)
Producers	Italy (87,042)	France (67,886)	Greece (58,601)	Spain (56,243)
Processors	Italy (24,844)	Germany (21,915)	France (20,493)	Spain (6,174)
Retail sales	Germany (€16.9 billion)	France (€12.2 billion)	Italy (€5.2 billion)	Spain (€2.7 billion)
Growth rate	Luxembourg (20.2%)	Hungary (13.9%)	Belgium (11.7%)	Sweden (6.7%)
Organic share of the total market	Denmark (11.6%)	Austria (11.4%)	Luxembourg (9.0%)	Sweden (6.7%)
Per capita consumption	Denmark (€373)	Austria (€292)	Luxembourg (€254)	Germany (€204)

Source: based on data from FiBL

Over the past decade, the retail value of organic food in the EU has more than doubled. At the end of 2024, the EU organic food market was worth close to €50 billion, an increase of 3.6% relative to the previous year, with an average growth rate of this market of 8.8% over the period 2014-2024 (Table 1). Following a period of slower market growth caused by the global economic crisis, faster growth that began in 2014 continued in subsequent years, reaching a high of 16.3% by the end of 2020. After 2020, the market experienced a marked slowdown and a decline in organic food sales as a result of several factors, including the war in Ukraine, high energy costs, and rising living costs.

Table 2 also provides an overview of the leading EU countries according to additional market criteria, such as market size, growth rate, per capita consumption, and the share of organic products in the total market. The largest market for organic food products was Germany, with a turnover of €16.9 billion, followed by France (€12.2 billion) and Italy (€5.2 billion). The market with the highest growth rate was Luxembourg

(20.2%), followed by Hungary (13.9%) and Belgium (11.7%), which managed to achieve double-digit growth rates in 2024. A reliable indicator of market development is annual per capita consumption of organic food. By this indicator, Denmark, together with Switzerland, can be considered a global leader. Annual per capita consumption of organic food in Denmark stands at €373, while Austria, with €292, and Luxembourg, with €254, rank second and third. These three countries are also the countries with the highest market share of organic products relative to other food products, ranging from 9% to 11.6% (Table 2). Among the categories of organic products, EU consumers spend most of their money on eggs, fresh fruit and vegetables, and milk and yoghurt. Fresh organic fruit and vegetables account for a share of over 10% of the organic market in Austria, Belgium, and Denmark; eggs account for a share of as much as 41% of the Danish organic market, while milk and yoghurt account for over 20% of total sales of organic products in Austria and Denmark (Willer et al., 2026, p. 211).

In the EU, most consumers do not purchase organically sourced products on a regular basis. According to a study conducted in the French market, only 37% of organic food buyers purchase these products regularly (daily or weekly). This means that a narrow core of loyal consumers generates most of the organic food turnover (Willer & Lernoud, 2018, p. 150). Another feature shared by EU consumers concerns the motives for, and barriers to, purchasing organic food. Many studies from EU countries (the Netherlands, Poland, Italy, Denmark, and Romania) identify health as the main motive for purchasing organic food products, showing that most consumers buy these products for health reasons (Schifferstein & Oude Ophuis, 1998; Bryla, 2016; Chinnici et al., 2002; Magistris & Gracia, 2008; Squires et al., 2001; Petrescu et al., 2017). Besides health, the absence of pollutants and chemicals, as well as concern for environmental protection, are also reasons that strongly motivate consumers to buy organic food, as is the case with Belgian, Norwegian, Danish, Swedish, Irish, and German consumers (Aertsens et al., 2011; Torjusen et al., 1999; Ekelund, 1990; Davies et al., 1995; Von Alvensleben, 1998). Consumers in Czechia, Spain, Italy, and Croatia report that price is the main barrier to purchasing and increasing their consumption of organic food (Magnusson et al., 2001; Zagata, 2014; Vega-Zamora et al., 2014; Janssen, 2018; Zanoli & Naspeti, 2002; Radman, 2005). Another important barrier to purchasing organic food in the Greek and Polish markets, as well as among regular consumers in Denmark and Italy, is limited availability (Fotopoulos & Krystallis, 2002; Bryla, 2018; Jensen et al., 2011).

Financial Instruments Supporting Organic Food Production in the EU

State support for organic agriculture can be viewed through three basic instruments (Stolze & Lampkin, 2009): legal, financial, and communication instruments. This paper focuses solely on analysing financial support instruments. The basic form of financial support for organic agriculture in all EU member states is area-based payments for conversion to, and maintenance of, organic production. This form of financial support has contributed to the expansion of organic agriculture in the EU, which is why payment rates rose in the 2014-2020 programming period relative to the previous 2007-2013 programming period. In some countries, such as Germany, Italy, and Denmark, area-

based payments rose considerably, while they remained unchanged only in Sweden and Slovakia. Depending on the land-use category, the highest payment rates in 2019 were identified as follows: (1) in Malta, for grassland and arable land – 209 €/ha for conversion and €555/ha for maintenance of organic production; (2) in Spain, Germany, Italy, and Belgium, for annual vegetables and herbs – maximum payments exceed €1,000/ha for conversion and €900-1,000/ha for maintenance of organic production; (3) in Germany, for protected cropping – €415-6,000/ha for conversion and €300-3,800/ha for maintenance of organic production; (4) in Belgium, Germany, Italy, and Luxembourg, for perennials, orchards and fruits – maximum payments reach over €1,000/ha for conversion and €800-975/ha for maintenance of organic production; (5) in Germany, for vineyards – €750-2855/ha for conversion and €675-2855/ha for maintenance of organic production; and (6) in Malta, Italy, and Slovenia, for olives – maximum payments range from €900-1209/ha for conversion and €677-810/ha for maintenance of organic production (Lampkin & Sanders, 2022).

The total budget allocated to support organic agriculture under the Common Agricultural Policy (CAP) 2014-2020 amounted to €6.3 billion, or 6.4% of the total rural development budget in the EU-28 (Katto-Andrighetto et al., 2017). For the following five-year period, 2023-2027, the planned budget for supporting organic agriculture amounts to more than €16 billion, representing 5% of total CAP expenditure and 20% of expenditure on environmental protection measures (Willer et al., 2025, p. 216). The data in Table 3 indicate that EU member states plan to support organic agriculture with more than €3.3 billion in annual payments by 2027/28, an increase of 85% relative to 2018, when they invested more than €1.8 billion. EU member states plan to double the supported area of organic agricultural land in the EU over the period 2018-2027. In 2018, annual payments for conversion to, and maintenance of, organic production covered 8.4 million ha of land, while for 2027/28 an increase in supported area of 93% is planned, which would bring the supported area to 16.4 million ha. In addition, average expenditure per hectare is expected to decrease by 5% in 2027/28 relative to 2018. Observed at the national level, and based on the data presented in Table 3, the following can be noted:

- With the exception of Estonia, Italy, and Sweden, an increase in total annual expenditure on support for organic agriculture is planned in the remaining EU member states. The highest expenditure in 2018 was recorded in Italy (386 million €), while the highest expenditure planned for 2027/28 is in France (603 million €);
- In most EU countries, payments per hectare are planned to increase relative to the previous programming period, significantly so in some countries, such as Malta. In 2018, average expenditure per hectare was highest in Cyprus (€805/ha), while by 2027/28 the highest expenditure per hectare is planned to be in Malta (€3,913/ha).
- In all EU member states except Estonia, an increase in the supported area under organic production is planned. In 2018, the largest total supported area of agricultural land was in Germany (1,150 kha), while by 2027/28 the largest supported area is planned to be in France (3,384 kha);

Table 3. Comparative overview of expenditure supporting organic agriculture in 2018 and planned expenditure for 2027/28.

	Expenditure (M€)			Expenditure/ha (€)			Supported area (kha)		
Country	**2018**	**2027/28**	**Relative**	**2018**	**2027/28**	**Relative**	**2018**	**2027/ 28**	**Relative**
Austria	121	154	127%	234	252	107%	515	610	118%
Belgium	19	46	238%	243	281	116%	80	163	205%
Bulgaria	24	101	416%	354	503	142%	68	200	293%
Cyprus	4	5	143%	805	459	57%	5	11	250%
Czechia	53	105	198%	105	140	134%	506	750	148%
Germany	300	553	184%	261	232	89%	1,150	2,384	207%
Denmark	41	74	181%	184	184	100%	223	403	181%
Estonia	18	6	30%	99	37	38%	186	150	81%
Spain	159	169	106%	152	134	88%	1,045	1,257	120%
Finland	56	90	160%	205	155	76%	274	580	212%
France	180	603	335%	173	178	103%	1,040	3,384	325%
Greece	97	259	267%	390	306	78%	248	846	340%
Croatia	33	63	191%	350	226	65%	94	279	296%
Hungary	21	63	294%	186	226	121%	115	279	296%
Ireland	8	89	1,116%	111	265	239%	72	337	468%
Italy	386	298	77%	352	200	57%	1,098	1,489	136%
Lithuania	36	64	175%	197	205	104%	184	309	168%
Luxembourg	1	8	656%	258	342	133%	5	24	494%
Latvia	28	33	117%	107	89	83%	261	368	141%
Malta	0.002	1	43,639%	374	3,913	1,045%	0.01	0	4,175%
Netherlands	0	22	∞	0	200	∞	0	109	∞
Poland	47	250	530%	138	380	275%	342	659	193%
Portugal	25	86	338%	124	125	101%	206	689	193%
Romania	42	57	133%	232	190	82%	183	298	163%
Sweden	75	73	97%	211	167	79%	355	437	123%
Slovenia	10	22	228%	210	269	128%	46	82	178%
Slovakia	17	36	212%	108	134	124%	158	270	171%
EU27	1,803	3,329	185%	213	203	95%	8,460	16,369	193%

Source: Lampkin, 2023

Materials and methods

The information basis for this research is the FiBL database, together with the data presented by Lampkin (2023) in the report Policy support for organic farming in the European Union 2010-2020 (Table 4). The analysis covers data from 2018 for indicators of financial support, as well as data from 2019 and 2023 for the share of organic land in total agricultural land[6]. The main objective of the research is to examine the role and importance of financial support, both in total amount and per hectare, for the growth of the area under organic production in EU member states. The effect of financial support

6 Data for the period 2020-2022 were excluded due to the negative impact of the global COVID-19 pandemic on the development of organic agricultural production worldwide.

on the expansion of organic areas is considered in the short term, taking into account the percentage of organic areas already in the following year, 2019, and in the longer term, observing the percentage of organic areas at the end of 2023. In pursuing this research objective, the following research questions were formulated:

1) Do higher total annual expenditures on support for organic agriculture contribute to a higher share of organic land in total agricultural land in EU member states?
2) Do higher average expenditures per hectare of supported organic land contribute to a higher share of organic land in total agricultural land?
3) What are the threshold values of annual total and average expenditure that separate countries with a higher share from countries with a lower share of organic land in total agricultural land?

Answers to these questions can help in assessing current, and planning future, financial support for organic agriculture, given that the "Farm-to-Fork" strategy envisages that at least 25% of agricultural land in the EU should be under organic production by 2030 (European Commission, 2020). The research questions are tested below using correlation analysis, a paired t-test, and a ROC curve.

Table 4. Variables — annual expenditure on organic agriculture (total and per hectare) and the share of organic land in total agricultural land, by EU member state

Country	Expenditure (M€)	Expenditure/ha (€)	Organic share of total agricultural land	
	2018	2018	2019	2023
Austria	121	234	26.1%	27.3%
Belgium	19	243	6.9%	7.5%
Bulgaria	24	354	2.3%	2.9%
Cyprus	4	805	5.0%	7.7%
Czechia	53	105	15.4%	16.9%
Germany	300	261	9.7%	11.3%
Denmark	41	184	10.9%	11.6%
Estonia	18	99	22.3%	22.9%
Spain	159	152	9.7%	12.2%
Finland	56	205	13.5%	13.7%
France	180	173	7.7%	9.6%
Greece	97	390	8.7%	17.6%
Croatia	33	350	7.2%	8.0%
Hungary	21	186	5.7%	6.4%
Ireland	8	111	1.6%	4.0%
Italy	386	352	15.2%	18.7%
Lithuania	36	197	8.1%	8.5%
Luxembourg	1	258	4.4%	6.3%
Latvia	28	107	14.8%	15.1%
Malta	0.002	374	0.5%	0.6%
Netherlands	0	0	3.8	4.8%
Poland	47	138	3.5%	4.4%

Country	Expenditure (M€)	Expenditure/ha (€)	Organic share of total agricultural land	
	2018	2018	2019	2023
Portugal	25	124	8.2%	21.7%
Romania	42	232	2.9%	5.1%
Sweden	75	211	20.4%	18.3%
Slovenia	10	210	10.4%	11.3%
Slovakia	17	108	10.3%	13.7%

Source: FiBL; and Lampkin, 2023

Results and Discussions

To determine whether a statistically significant association exists between the variables under consideration — total expenditure on organic agriculture in 2018, expenditure per hectare of supported organic land in 2018, and the share of organic land in total agricultural land in 2019 and 2023 — a correlation analysis was carried out. The association was examined using Spearman's rho coefficient, given that, according to the results of the Shapiro-Wilk normality test, normality of distribution was not confirmed for total expenditure and expenditure per hectare ($p=0.000<0.05$). Values of Spearman's correlation coefficient range from -1 to +1, where values from 0.1 to 0.29 indicate a weak correlation, values from 0.30 to 0.49 indicate a moderate correlation, and all values above 0.50 up to 1 indicate a strong positive correlation (Pallant, 2011).

Table 5 shows the results of the correlation analysis which finds a strong positive correlation between total expenditure on organic agriculture in 2018 and the share of organic land in total agricultural land in 2019 ($\rho=0.501$, $p=0.008< 0.05$) across 27 EU countries. The correlation analysis also showed a statistically significant moderate association between total expenditure on organic agriculture in 2018 and the share of organic land in total agricultural land in 2023 ($\rho=0.490$, $p=0.009<0.05$). The analysis did not confirm a statistically significant association between expenditure per hectare in 2018 and the share of organic land in total agricultural land in 2019 ($p=0.246>0.05$), nor with the share of organic land at the end of 2023 ($p=0.478>0.05$). The results obtained also confirmed a strong positive correlation between the share of organic land in total agricultural land in 2019 and in 2023 ($\rho=0.905$, $p=0.000<0.05$).

Table 5. Correlation matrix

Variables	Expenditure (mil euro) 2018.	Expenditure (ha/ euro) 2018.	Organic shares of total agriculture land 2019	Organic shares of total agriculture land 2023
Expenditure (mil euro) 2018.	1.000	.118	.501**	.490**
Expenditure (ha/ euro) 2018.	.118	1.000	-.231	-.143
Organic shares of total agriculture land 2019	.501**	-.231	1.000	.905**

Variables	Expenditure (mil euro) 2018.	Expenditure (ha/ euro) 2018.	Organic shares of total agriculture land 2019	Organic shares of total agriculture land 2023
Organic shares of total agriculture land 2023	.490**	-.143	.905**	1.000

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

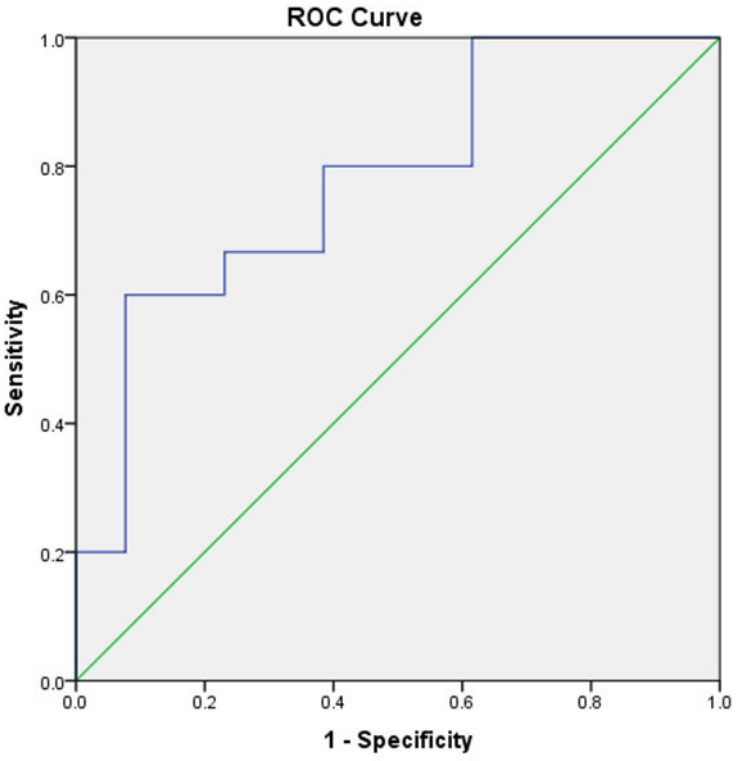
Source: Authors' calculations

Over the period 2019-2023, the share of organic land in total agricultural land increased in almost all EU countries observed. Whether this difference is also statistically significant is shown by the results of the paired t-test. In 2019, the average share of organic land in total agricultural land across the 27 EU countries was 9.44% (SD=6.38%), while the average share of this land in 2023 was 11.67% (SD=6.57%). The results of the t-test show that the 2.23-percentage-point difference between the share of organic land in total agricultural land in 2019 and 2023 is statistically significant ($p=0.002<0.05$). This significant increase in the share of organic land in 2023 could plausibly be linked to the total investment (in millions of euros) made in 2018.

For this purpose, a ROC curve (Receiver Operating Characteristic Curve) was applied, linking sensitivity (the probability of correctly detecting the presence of a trait) and specificity (the probability of incorrectly detecting the presence of a trait). Each point on the ROC curve represents an ordered pair (sensitivity, 1-specificity) corresponding to an individual value of the variable. For ROC analysis to be applied, the dependent variable must be dichotomous. Accordingly, two new variables were constructed referring to the share of organic land in total agricultural land: a share of less than 10%, coded as zero (0) and indicating countries with a lower level of development of organic agriculture, and a share of more than 10%, coded as one (1), representing countries with a higher level of development of organic agriculture. When examining the results of a given test for these two constructed populations of EU countries, it is very rarely possible to achieve complete separation between the two. In such cases, the separation should be based on the value of some continuous random variable (e.g., expenditure on organic agriculture in millions of euros), by determining the cutoff that best separates the two populations. One way of determining the cutoff is to take the value of the variable at which the difference between sensitivity and 1-specificity is maximal. A variable is better suited for testing, that is, for distinguishing countries with a higher share from countries with a lower share of organic land, the larger the area under the ROC curve (AUROC). The closer the area is to 0.5, the less suitable the variable is as a marker, while the closer it is to 1, the more suitable it is as a marker. To determine whether total expenditure on organic agriculture for 2018 can serve as a good marker for classifying countries into the group with a share of organic land in total agricultural land above 10%, data for 2019 were used first. The results for 2019 were not statistically significant (Area=0.618, $p=0.315>0.05$), which can be explained by the fact that, although a positive correlation exists, 2018 expenditure could not yet produce positive results in terms of increasing the share of organic land as early as

the following year. The share of organic land in total agricultural land in 2023 was therefore taken in the next step, with countries classified into two groups in the same way. Besides numerical values, the results of the ROC analysis also provide a graphical interpretation of the findings (Figures 1).

Figure 1. ROC curve



Source: Authors' calculations

The results obtained show that total expenditure on organic agriculture (in millions of euros) in 2018 can serve as a good marker for classifying countries into the group that will have a share of organic land in total agricultural land above 10% (area = 0.764, p=0.020<0.05) (Table 6). The value of total annual expenditure of €50 million was obtained as the optimal cutoff point separating countries into these groups (a share of organic land >10% and a share of organic land <10%). Based on this cutoff, Table 7 was constructed, showing the number of countries according to the optimal cutoff point and the share of organic land.

Table 6. Area under the curve

Area	Std. Error	Asymptotic Sig.[b]	Asymptotic 95% Confidence Interval	
			Lower Bound	Upper Bound
0.764	0.093	0.020	0.581	0.947

Source: Authors' calculations

Table 7. Number of countries according to the optimal cutoff point and the share of organic land in total agricultural land

	Organic shares of total agriculture land < 10% 2023	Organic shares of total agriculture land > 10% 2023
Expenditure < 50 million euro	12	6
Expenditure > 50 million euro	1	8

Source: Authors' calculations

Table 7 above shows that:

$$\text{Sensitivity} = 8/(8+6)=0.571=57.1\%$$

$$\text{Specificity} = 12/(12+1)=0.923=92.3\%$$

$$\text{Positive predictive value} = 8/(1+8)=0.889=88.9\%$$

$$\text{Negative predictive value} = 12/(12+6)=0.667=66.7\%$$

The positive predictive value of 88.9% means that eight of the nine countries with annual expenditure above €50 million had an organic land share above 10% in 2023. The negative predictive value of 66.7% means that 12 of the 18 countries below this threshold had a share under 10%, while the other six exceeded 10%. Expenditure above €50 million predicts a higher organic land share better than expenditure below it predicts a lower one. The sample is small (27 countries), so the results are preliminary.

Conclusions

The EU is one of the largest organic food markets in the world, recording high growth rates and increasing per capita consumption of organic products. Alongside continuous growth in demand, the area under organic production in EU countries is also expanding, supported by financial instruments in the form of payments for conversion to, and maintenance of, organic production. EU member states generally allocate a significant budget to support organic agriculture, which increases considerably with each successive programming period. Nevertheless, the EU organic market is heterogeneous, both in terms of total and relative expenditure on organic agriculture and in terms of the representation of organic land in total agricultural land. The findings obtained indicate that differences in the share of organic land may be caused by the level of total annual expenditure on organic agriculture. In those EU member states that have higher total

annual expenditure on organic agriculture, an increase in the share of organic land in total agricultural land occurred over the longer term. A particular contribution of the analysis is that it reveals that once total annual expenditure on organic agriculture at the national level exceeds €50 million, the probability that the share of organic land in total agricultural land will exceed 10% increases. This means that EU member states must continuously increase their annual budget above the threshold value of €50 million in order to raise the share of organic land above the EU average and move closer to the planned target of 25% of land under organic production by 2030. The main limitation of this study relates to the period observed, since the indicators analysed come from the previous programming period, so future research should cover data from the current programming period. In addition, in examining the effect on the growth of the share of organic land, alongside financial support instruments, future research could include other factors such as legal and communication instruments. Future research should also apply other statistical methods, such as regression analysis.

Conflict of interests

The authors declare no conflict of interest.

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ECONOMIC AND LEGAL ANALYSIS OF FOOD BIO-FRACTION MANAGEMENT IN THE CONTEXT OF CIRCULAR AGROECONOMY AND THE GREEN AGENDA FOR THE WESTERN BALKANS

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ABSTRACT

The paper conducts an economic and legal analysis of food bio-fraction management in the context of the transition towards a circular agroeconomy and the requirements of the Green Agenda for the Western Balkans. The research focuses on the role of consumers in a sustainable agri-food system and their willingness to separate and collect food bio-waste. The empirical research was carried out on a sample of 692 respondents, utilizing descriptive statistics and multiple linear regression. The findings indicate that financial reciprocity, accessible infrastructure, and greater institutional trust constitute prerequisites for transforming citizens from passive users into active participants in the circular agroeconomy and closing the nutrient loop in the food chain. This implies a need for local policies that combine economic incentives, clearly defined legal obligations, and programs for donating edible surpluses and food waste, in line with the principles of the Green Agenda.

Introduction

National legislation and EU regulations clearly mandate restrictions on landfilling biodegradable waste, aiming to reduce both waste volumes and greenhouse gas emissions generated by the decomposition of organic waste (Batinić, 2015). The degradation of

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biodegradable waste releases phytotoxins, carbon dioxide, salt, and heat, resulting in severe environmental and health consequences. Food loss encompasses edible food that is lost or damaged during production, storage, processing, and distribution before reaching the consumer, with a significant portion of these losses occurring in urban areas. The key to efficient food bio-fraction management lies in prioritizing the source-separation, collection, and treatment of household waste, particularly the food fraction. Proper treatment of food waste significantly contributes to reducing methane emissions generated by anaerobic decomposition in landfills, whereas composting represents a sustainable alternative that yields high-quality compost, supports resource conservation, and contributes to a sustainable agricultural system (Vukadinović, 2018) and agricultural land regeneration through the return of organic matter and nutrients.

The source-separation and treatment of biodegradable waste reduce the volume of waste ending up in landfills, extend their lifespan, and mitigate negative environmental impacts, while simultaneously creating resources from waste. Food bio-fraction separation and composting benefit numerous local communities on ecological, economic, and social levels. In this context, landfill capacity planning and the development of regional sanitary landfills and waste treatment facilities also entail the establishment of transfer stations to ensure the cost-effective transport of waste over longer distances.

The food bio-fraction management challenges have become more pronounced due to the increasing volume of waste and rising labor and system maintenance costs. In many developed countries, 50–70% of total waste management expenditures are attributed to collection and transport; therefore, even relatively small improvements in collection logistics can significantly reduce overall system costs (Pešević, 2022). Beyond technical and infrastructural solutions, cities can establish partnerships with local organizations, schools, and communities to develop food loss reduction initiatives tailored to local specificities. Particular attention should be directed toward preventing food waste and reducing losses through systems that donate surplus edible food to food banks, which subsequently distribute it to the population—thereby simultaneously reducing waste and supporting socially vulnerable groups. Additionally, local policies can facilitate food donation through tax incentives and other benefits for donors, while collaboration with retail chains can yield programs for distributing perfectly edible products that would otherwise end up as waste.

Gustavsson et al. (2011) state that approximately one-third of all food intended for human consumption is lost or wasted, amounting to a total of 1,3 billion tonnes of food annually. Since food production requires substantial resources, food loss and waste indirectly lead to various negative environmental impacts, including soil erosion, deforestation, water and air pollution, as well as the generation of greenhouse gases during production, storage, transport, and waste management processes (Mourad, 2016). It is precisely due to these growing ecological, social, and economic challenges that the issue of food waste is increasingly recognized as urgent and critical among governments, the business community, non-governmental organizations, researchers, and the general public.

Certain authors (Zadik & Katz, 2025; Ekström, Bjorvatn & Sjåstad, 2024; Đorić, 2022) are of the opinion that economic incentives and nudges can powerfully alter household behavior toward source-separation, recycling, and composting, whereas behavioral changes must be designed by respecting cognitive limitations and social norms, rather than relying solely on appeals to ecological awareness. Individuals are often unaware of externalities—specifically, the costs borne by society through the public budget—because these costs remain invisible and underestimated by citizens. Consequently, there is a need to raise awareness about the real costs of waste, as well as to reshape perceptions and habits, while public policy should engage households more actively (via pricing strategies, fees, pay-as-you-throw systems, vouchers, composting support, etc.).

Serbia faces significant challenges regarding landfilling as well as recycling and composting capacities, while its waste separation systems, billing mechanisms, and infrastructure remain under development (World Bank, 2024). Previous research has predominantly adopted a macro-analytical approach to system financing, focusing on waste volumes and composition, household food waste management and its behavioral shifts during the pandemic, waste generation, purchasing habits, willingness to reduce food waste, and the infrastructural and institutional aspects of waste management (such as waste quantities, landfills, system development plans, and service financing). However, there is a distinct lack of research in Serbia regarding household behavior in response to small financial incentives for source-separation, recycling, and composting, as well as the impact of normative messages, institutional trust, neighborhood cohesion, informal networks, and the willingness to pay (WTP) for enhanced waste management services.

The Sofia Declaration on the Green Agenda for the Western Balkans emphasizes that this document is dedicated to the process of transitioning from a linear to a circular economy, while recognizing the need for research and innovation systems to support this transition. In order to contribute to environmental protection and minimize the volume of waste generated in the region, the Green Agenda promotes a plan to integrate the Western Balkans into EU industrial supply chains. This is to be achieved, inter alia, by developing circular economy strategies that consider the entire product lifecycle, waste prevention, modern waste management and recycling, reuse, repair, and remanufacturing, as well as through further progress in constructing and maintaining waste management infrastructure for cities and regions. In fact, from a legal standpoint, the core of the Green Agenda for the Western Balkans in the context of food waste rests on the obligation to align the national legislations of the region's countries with the European Union *acquis*, aiming for a full transition from a linear to a circular economic model. The Western Balkan countries have committed to transposing the provisions of the EU Waste Framework Directive (Directive 2008/98/EC) into their domestic legal frameworks governing waste management. Therefore, the objective of adopting a new—or amending the existing—legal framework regarding waste regulation is to transform waste from an environmental burden into an economic resource through strict statutory regulation and, among other things, to establish a sustainable bio-waste management system in line with European Union standards.

In 2025, Serbia adopted a new Waste Management Act. The structure of the new statutory text differs significantly from the previous law enacted in 2009. The key objectives of the new Act are deeper alignment with European Union directives, the digitalization of the system, and the strengthening of inspection oversight. As an example, and within the context of this paper's research scope, the new 2025 statutory text introduces and defines a new concept, namely "food waste"; furthermore, it permits the import of non-hazardous waste for energy recovery purposes, mandates electronic record-keeping and the digitalization of waste movement tracking documents, and significantly tightens extended producer responsibility (EPR) through clearer financial and legal provisions. Nevertheless, it remains evident that the new Waste Management Act is not fully aligned with European Union standards. Many provisions of the new Act, which acts as the *lex generalis* in waste management matter, require precise secondary legislation (decrees and rulebooks) to properly define and regulate this field in greater detail.

Due to the fact that prior research has not addressed the combination of economic and behavioral instruments, the research scope of this paper is to analyze the impact of economic, infrastructural, regulatory, and behavioral-cognitive factors, with the aim of investigating their influence on citizens' willingness to actively participate in food waste source-separation. In accordance with the research of Zadik & Katz (2025), Ekström et al. (2024), Thøgersen (2003), Thaler & Sunstein (2008), Fullerton & Kinnaman (1999), Prelez et al. (2023), Jalalipour et al. (2025), Herath & Meyler (2017), Krause et al. (2023), Omar & Rohani (2015), Qasim et al. (2020), Svensson & Karlsson (2024), Matzembacher et al. (2020), Al Habsi et al. (2026), Kosters & Van der Heijden (2015), Đorić (2022), Vukadinović (2018), Živković et al. (2021), Rai et al. (2025), Schanes et al. (2018), Russell et al. (2017), and the empirical findings of Berjan et al. (2022) for Serbia, the baseline hypothesis is formulated as follows: 1. Economic instruments, namely financial incentives (direct rewards — utility bill reductions; systemic inducements — vouchers and points; and personal economic benefits — budget savings); 2. Infrastructural and regulatory factors, namely the role of the system (infrastructural support — free dedicated bins/containers; punitive policies — the strictness of the law); 3. Behavioral-cognitive factors, namely awareness and knowledge (macroeconomic awareness — knowledge of landfill damages; circular value — understanding waste as a raw material), influence citizens' willingness to actively participate in food waste source-separation and collection.

Linking the Concept of Circular Economy with the Role of the Individual/ Household Behavioral Economics

Preventing food losses at the consumer level directly conserves the resources invested in primary agricultural production (land, water, energy, and mineral fertilizers), thereby establishing the principles of a circular agroeconomy. The food bio-fraction management can be addressed from technological, ecological, legal, and economic perspectives, as well as through the lens of human behavior and decision-making processes. Economic incentives and "nudges" (such as utility bill reductions, discounts on composting

equipment, or rewards for source-separation) can appeal to individual responsibility, acting as stimuli that redirect household behavior toward composting and recycling (Zadik & Katz, 2025; Ekström, Bjorvatn & Sjåstad, 2024). According to Đorić (2022), ecological incentives lead to a departure from the collective dimension of environmental protection, shifting collective responsibility onto individuals. Simultaneously, they appeal to rational self-interest (lower costs, financial gains) and leverage psychological mechanisms, behavioral patterns, and beliefs—collectively referred to as behavioral economics. In order to transition from traditional waste disposal to composting or recycling, the system must be designed in a way that highlights the correct decision as the easiest and most cost-effective option. Relying solely on social norms and environmental awareness is insufficient; rather, residents need to perceive the shortcuts and advantages of such behavior. Research by Cardadeiro, Laneiro & Roseta-Palma (2023) has demonstrated that messages framed around social norms in the form of descriptive norms yield positive results. According to Lima & Branco (2018), descriptive social norms are expected to influence behavior, with social identity moderating these associations. A promotional message phrased as "Join your neighbors..." proved to be more effective than a typical appeal to environmental protection or self-interest.

Through local actions (e.g., introducing discounts or providing free composting equipment, training, and technical support), the state can lower adoption barriers and encourage the desirable and expected behavior of individuals, targeting issues such as equipment costs, lack of knowledge, and process uncertainty (Jalalipour et al., 2025). Research by Chernet, Sema, Gebeyehu & Wogayehu (2024) indicates a willingness among households to pay for improved solid waste management. They conclude that municipalities should leverage this willingness by establishing enhanced waste management systems, which can help alleviate budgetary constraints through active household participation in financing these services.

Empirical research by Zadik & Katz (2025) indicates that small rewards doubled the amount of source-separated waste, meaning that monetary incentives—even in small amounts—stimulate higher household participation in waste separation (Svensson & Karlsson, 2024). A similar effect is observed with pay-as-you-throw (PAYT) systems and recycling rewards. In addition to increasing the volume of recycled waste, this approach alters the motivational structure, thereby reshaping how waste is perceived (Thøgersen, 2003). While a segment of households responds directly to financial incentives (Al Habsi, Huang & Liu, 2026), another develops a sense of personal environmental responsibility. In an extensive field study, Ekström, Bjorvatn & Sjåstad (2024) compared small price-stimuli with normative nudges and concluded that small pricing incentives exert a large, lasting positive effect on both the quantity and quality of recycling, whereas the normative nudge alone shows no statistically significant effect. A study by Prelez, Wang & Shreedhar (2023) demonstrated that small monetary factors have a stronger and more sustained effect; consequently, individuals no longer perceive recycling as a burden or an extra chore, but rather as a contribution to the household budget. This bridges the intention-action gap, transforming waste separation, recycling, and/or composting into financial

savings, where every unutilized liter or kilogram is perceived as a cost. Since waste management costs are covered by the public budget, any expenditure that could have been prevented through recycling or separation represents a loss that could have otherwise financed public goods consumption. Therefore, economic incentives (e.g., reduced utility bills for those who compost) are particularly significant. Thaler & Sunstein (2008) state that nudges steer people's behavior in a predictable direction without forbidding any options or significantly changing their financial incentives. Although nudging has become popular in public policies aimed at reducing energy, water, and paper consumption, as well as mitigating food waste, it has faced criticism due to potential manipulation and a lack of long-term evaluations (Kosters & Van der Heijden, 2015).

The theory of externalities indicates that certain costs impact a third party—that is, a participant who did not choose to be involved in the process. These include landfilling costs, greenhouse gas emissions, and infrastructure and health burdens, which are borne by the city through the public budget rather than by individual households. Krause, Kenny, Stephenson & Singleton (2023) point to the first in a cascade of costs associated with food waste that ends up in a landfill instead of a composter. During the decomposition of food in landfills, methane is released—a gas that is over 25 times more potent than CO2 at trapping heat, consequently driving climate change. In the EU, more than 58 million tonnes of food waste are generated annually, with an estimated market value of 132 billion euros (UBQ Materials, 2024). Toxic liquid (leachate) contaminates water resources, forcing municipalities to invest millions into wastewater treatment facilities and soil protection (Omar & Rohani, 2015). Food waste is heavy, thereby requiring more trucks, higher fuel consumption, and the rapid depreciation of road infrastructure, ultimately leading to the necessity of constructing new, prohibitively expensive landfill cells. Organic waste landfills attract rodents and insects that act as disease vectors, increasing the incidence of respiratory and infectious diseases in nearby areas, which directly strains the public healthcare system (Qasim et al., 2020; Maheshwari, Gupta & Das, 2015). The transport of municipal waste is also linked to negative effects on property values, community image, and aesthetics, while causing noise, unpleasant odors, and traffic congestion (U.S. EPA, 1997).

One of the objectives of waste management policy is to inform individuals about the real costs of waste, thereby prompting them to change their habits (Fullerton & Kinnaman, 1999). According to the theory, externalities are often hidden and thus underestimated costs, yet they are associated with massive social costs. In order to make acceptable political decisions regarding food waste management, it is essential to properly identify, understand, and assess such externalities (Herath & Meyler, 2017).

In promoting pro-environmental behavior (Sörqvist, 2016), environmental psychology begins by studying and explaining the complex relationships between people and their natural or built environments. Four key stages have been identified: identifying the behavior to be changed; examining the main factors underlying that behavior; designing the behavioral intervention; and evaluating the effects of implementation (Steg & Vlek, 2009). Kahneman (2003) points out that humans possess limited cognitive capacities,

imperfect willpower, and bounded self-interest; therefore, a thorough understanding of cognitive shortcuts (heuristics), information framing, and loss aversion can significantly improve the design of public policies.

Materials and methods

The empirical research was conducted on a sample of urban consumers in the territory of the city of Novi Sad, aiming to understand the role and behavior of end consumers in the agri-food chain and food waste management. This empirical segment investigated the perspective of citizens, specifically focusing on the role of individuals in managing food waste. The research sample consists of 692 randomly selected respondents whose answers were included in the subsequent analysis. The survey was designed using Google Forms, and the questionnaire link was distributed utilizing the snowball sampling method. A total of 822 invitations were sent out, yielding responses from 692 participants, which represents an 84.18% response rate. A list of specially formulated questions was prepared for the survey, strictly aligned with the established research objectives.

The first section of the questionnaire covers the socio-demographic characteristics of the respondents. The second section focuses on the specific food-related behavior of the respondents (9 questions) and the relationship between motivation and knowledge (4 questions). The third section addresses: environmental awareness and attitudes toward food waste (5 questions); intentions and willingness to participate (5 questions); the role of social norms and networks (7 questions); perceptions of the institutional and regulatory framework (7 questions); and the assessment of responsibility and reasons for non-compliance in food waste management (3 questions). Thus, the research objective was to construct a profile of the individual handling food waste, understand their specific behaviors, and thereby formulate recommendations, promotional messages, and regulatory measures regarding food waste.

Given that the Google Forms questionnaire was configured to ensure that no questions could be skipped and that all fields required precise completion in compliance with the prompts and instructions, data cleaning or the exclusion of incomplete questionnaires was unnecessary. Furthermore, preliminary manual data sorting and tabulation were not required, as Google Forms enabled the automatic export of data into a unified Excel spreadsheet, which facilitated the seamless integration of the SPSS software for statistical data processing.

For the in-depth data analysis, descriptive statistics and multiple linear regression were employed. Descriptive statistics were used to describe the sample and identify trends, quantitatively presenting the research results through frequencies, percentages, and mean values. Multiple linear regression was applied to determine the prediction of habit changes in food waste management. In this manner, the impact of seven independent variables on citizens' willingness was examined; specifically, the analysis identified the influence of economic incentives, infrastructural and regulatory factors, as well as the significance of behavioral-cognitive drivers on changing habits in food waste management.

Results

Results The research results indicate that the sample is predominantly female, accounting for 61.6%, while the age structure is evenly distributed, with a slight dominance of the population aged 51 to 70 (36.8%). In terms of education, 76.9% of the respondents hold a higher education degree.

Table 1. Socio-demographic structure of respondents

		Frequency	Percent			Frequency	Percent
Gender	Female	426	61.6	Education	Master's/PhD	139	20.1
	Male	266	38.4		Secondary School (SSS)	160	23.1
Age	19-30	137	19.8		Higher Education (VS)	393	56.8
	31-50	138	19.9	Income	120 – 150 in 000 RSD	132	19.1
	51-70	255	36.8		50 – 80 in 000 RSD	135	19.5
	71+	136	19.7		80 – 120 in 000 RSD	258	37.3
	under 18	26	3.8		under 50 in 000 RSD	160	23.1
Residence	House	275	39.7		over 150 in 000 RSD	7	1
	Apartment	417	60.3				

Source: Authors' calculations

The high education level of the respondents corresponds to a high level of environmental awareness, as evidenced by the attitudes that: food bio-fraction separation is crucial for the environment (M=4.22; std. dev. 0.629), food waste constitutes a serious environmental problem (M=4.33; std. dev. 0.472), it is linked to climate change (M=3.78; std. dev. 0.415), and it represents an important segment of the circular economy (M=4.33; std. dev. 0.472). This high environmental awareness reflects emancipated citizens who demand public services from the state, given that they pay taxes and other levies. Their critical stance toward infrastructure in buildings or neighborhoods is associated with the perception that the level of living standards does not necessarily align with the level of environmental awareness.

An increase in consumption is linked to income growth; thus, higher purchasing power generates a larger ecological footprint. The respondents predominantly reside in apartments (60.3%) and possess solid incomes (37.3% have incomes ranging from 80k to 120k RSD). Consequently, there is greater "pressure" on the waste disposal system, given the generation of larger volumes of potentially recyclable waste, particularly the organic food bio-fraction (food deliveries, online shopping, cosmetics). Unlike respondents living in houses, who have easier access to composting, those residing in apartments are highly dependent on municipal infrastructure. As a result, the lack of source-separation containers challenges their environmental awareness and breeds frustration. The attitudes of respondents aged 51 to 70 (36.8%) hold particular significance and play a key role in interpreting the findings. Their views on waste disposal, separation, and recycling are linked to memories of a time when the collection system for secondary raw materials (glass packaging, waste paper in schools) was organized differently. Due to these comparisons with the past, they emerge as the most demanding segment of respondents.

Table 2. Specific household behavior regarding the food bio-fraction

	Mean	**Std.dev.**
In my household, we frequently discard cooked food leftovers.	2.08	.846
We often throw away fruits and vegetables because they spoil before we can use them.	2.38	1,08
When shopping, I frequently purchase more food than we actually need.	2.42	1,12
I usually save uneaten food and use it for the next meal.	4.20	.633

Source: Authors' calculations

The respondents expressed a high level of agreement regarding food preservation (M=4.20; std. dev. 0.633), indicating a tradition of minimizing food waste, reuse, and meal repurposing. Moderate incomes are associated with respondent responsibility; thus, the low mean values for statements concerning the discarding of cooked food leftovers (M=2.08; std. dev. 0.846) and throwing away spoiled fruits and vegetables due to underutilization (M=2.38; std. dev. 1.08) demonstrate that citizens in Serbia, according to this study, value the effort and resources invested in food preparation. On the other hand, discarding spoiled food or purchasing larger quantities constitutes a direct impact on the household budget, requiring planning and attention—particularly given the high participation rate of respondents with incomes up to 80k RSD.

Table 3. Environmental Intention and Actual Behavior

Do you source-separate your waste and dispose of it in the designated bins?	**Frequency**	**Percent**	**If you source-separate your waste, what is your primary motivation for doing so?**	**Frequency**	**Percent**
Yes, I do so every day.	118	17	I care about the environment.	119	17.2
No, because I lack the necessary infrastructure.	476	68,8	I care about the future.	60	8.7
I have never disposed of waste this way, even though I have access to a designated bin.	98	14.2	I do not source-separate.	394	56.9
			It makes me feel better.	60	8.7
			It gives me a sense of satisfaction.	59	8.5

Source: Authors' calculations

When examining the link between the respondents' awareness and their actual behavior, it is crucial to highlight that a high percentage of participants—specifically 68.8% (476 individuals)—do not source-separate waste because they lack the necessary infrastructure. When combined with the small proportion of those who do so every day (17%), it can be concluded that strong environmental intentions are hindered by an inadequate system. An analysis of the respondents' motivational structure indicates the presence of environmental concern as an ecocentric motive (17.2%), along with emotional satisfaction ("it makes me feel better" – 8.7% and "it gives me a sense of satisfaction" – 8.5%). Thus, the results indicate that for a small segment of the population, recycling has become embedded in their personal identity and moral

integrity rather than being perceived merely as a technical chore. Furthermore, the data reveals that 14.2% of the respondents represent the actual proportion of the population that is resistant to habit changes.

Table 4. Relationship between motivation and knowledge

		Frequency	**Percent**
Do you compost at home?	Yes	173	25
	No	346	50
	I would like to, but I do not know how.	173	25
Are you aware that developed countries collect coffee grounds from households and restaurants?	Da	58	8.4
	Ne	634	91.6
Are you aware that some countries collect used cooking oil?	Ne	576	83.2
	Da	116	16.8
If you had the opportunity, would you collect and hand over coffee grounds or used cooking oil?	Da	429	62
	Ne	263	38

Source: Authors' calculations

There is a visible gap between the respondents' knowledge, awareness, and motivation to adopt new environmental practices regarding coffee grounds and used cooking oil. According to the study, the collection of coffee waste and used cooking oil in Serbia is still in its infancy or is inadequately promoted. Nevertheless, the respondents demonstrated a strong willingness to collect these secondary raw materials, confirming their openness to new ecological concepts once the necessary conditions are established.

Table 5. Disposal Methods for Specific Raw Materials and Collection Models

		Frequency	Percent
In your estimation, how much used cooking oil waste does your household generate?	0 liters	174	25.1
	1 - 5 liters	518	74.9
In your estimation, how much coffee waste does your household generate?	0 -1 kg Monthly	480	69.4
	1 - 5 kg Monthly.	133	19.2
	0 kg Monthly	79	11.4
The most efficient method for collecting used cooking oil	By organizing annual, scheduled collection drives directly from households	232	33.5
	By placing specialized containers at recycling centers/ waste collection islands	460	66.5

Source: Authors' calculations

By examining the quantities of secondary raw materials (oil, coffee, and food) that are effectively lost from the system, it can be concluded that inadequate disposal occurs, leading to negative environmental impacts. Used cooking oil waste (with 74.9% of respondents generating between 1 and 5 liters monthly) and coffee waste (69.4% generating 0–1 kg per month) represents a clear environmental challenge

and underscore the necessity for a systemic solution. Regarding logistical solutions and preferred collection models, the respondents' feedback is highly significant for designing guidelines for local governments and public utility companies. The majority of respondents (66.5%) prefer the placement of specialized containers in the immediate vicinity of their residence, whereas the model of periodic campaigns (such as "eco-days") is supported by 33.5% of the participants.

Table 6. Environmental awareness, attitudes, intention, and willingness to participate in food bio-fraction separation

Environmental awareness and attitudes toward food bio-fraction separation	**Mean**	**Std. Dev.**
I believe that waste separation is important for the household budget (economic benefit).	3.95	.94
I believe that food waste represents a serious environmental problem (landfill economic damage / macroeconomic awareness).	4.41	.72
I am aware of the impact of food waste on the environment and climate change.	3.78	.415
I view food waste reduction as an important part of the circular economy – waste is a valuable raw material.	4.28	.81
Individuals are adequately sanctioned for improper disposal of waste and food waste?	1.50	.686
Intention and willingness to participate		
I am willing to separate food waste if a dedicated bin is provided near my home (infrastructural reward).	4.58	.065
I am willing to change my habits and separate food waste.	4,51	.68
Over the next year, I plan to pay more attention to the amount of food I waste.	3.56	.500
I am willing to participate in a local composting or food waste separation program in exchange for a reduced utility bill (direct reward).	4.62	.61
I am willing to support food surplus donation programs (e.g., through separation and awareness sharing).	4.67	.472

Source: Authors' calculations

The results presented in the table indicate a high level of awareness and environmental literacy, where food waste is recognized as a key element of the circular economy (M=4.28). Respondents identified a systemic deficiency, specifically the inadequacy of the penal policy and the absence of institutional control in this area (M=1.50). On the other hand, the respondents' willingness to participate is very high (M=4.58), provided that accessible infrastructure (bins near the home) is available. We are of the opinion that respondents are ready to change their personal habits (M=4.51), demonstrating a readiness to adapt, but they demand that the public utility system takes full initiative.

Table 7. Social norms and networks (norms, networks)

	Mean	**Std. Dev.**
Most people I know try hard not to waste food.	3.41	.492
People in my social circle separate waste (including food waste).	2.00	.674
It is important to me what others think about my attitude toward environmental protection.	2.96	.564
My family members encourage me to pay attention to the amount of food we waste.	3.68	.466
Through my social networks (relatives, friends, neighbors), I receive information on ways to reduce food waste.	2.50	.500
I feel a personal responsibility to reduce food waste in my household.	4.41	.492
I believe that a "good citizen" should separate food waste.	4.32	.465

Source: Authors' calculations

The respondents demonstrated a clear distinction between internal moral norms and the actual situation within their social networks. It is an established fact that the social environment shapes an individual's environmental behavior, and that social pressure or support influences waste management. The results indicate a high level of personal responsibility (M=4.41) and a strong belief that a "good citizen" should separate waste (M=4.32). Driven by an internal sense of proper behavior, respondents strive toward the ideal of a "good citizen" despite the absence of widespread waste separation, composting, and recycling. The role of the family (M=3.68) indicates that environmental awareness is primarily transmitted and sustained within the household; thus, regarding food waste, the family serves as a corrective factor to a greater extent than formal institutions do. The results further reveal that respondents do not receive sufficient information about waste reduction from their friends and neighbors (M=2.00), pointing to an existing social isolation in terms of environmental behavior. Since individuals lack information suggesting that their friends, relatives, and neighbors behave in this manner, they become isolated in their decision-making and may eventually abandon these practices over the long term. Although there is an acknowledged stance that the opinions of others matter (M=2.96), respondents do not recycle or conserve food for the sake of others or for public recognition, but rather due to their own sense of responsibility and household economics.

Table 8. Perception of the institutional and regulatory framework

	Mean	**Std. Dev.**
There are enough containers/bins for separate waste collection in my neighborhood.	2,34	1,16
The waste sorting system in my city is well-organized.	2.18	1,04
I believe that the competent institutions actually recycle the waste sorted by citizens.	2.00	.952
I believe that the introduction of a stricter penal policy is necessary for those who do not comply with waste disposal rules (penal policy).	3,82	1,22

	Mean	Std. Dev.
I believe that financial incentives (e.g., lower bills, rewards) would motivate citizens to separate food waste (systemic incentives).	4.35	.78
I support the introduction of local food waste composting programs.	4.49	.500
I support the introduction of a food surplus donation system (food banks) by grocery stores and restaurants.	4.85	.454

Source: Authors' calculations

The analysis of the institutional and regulatory framework highlights a gap between the current provision of public utility services and citizen expectations. Respondents rate the current infrastructure very poorly in terms of container availability (M=2.34) and the general organization of the system (M=2.18). Of particular concern is the skepticism and distrust among citizens regarding the recycling process (M=2.00), which undermines the effort invested and keeps primary source-separation at a low level. Implementing stricter penalties (M=3.82) received a lower score compared to the support for financial incentives (M=4.35), suggesting that while penalties are deemed necessary to establish order in public spaces, respondents view positive reinforcement (e.g., lower bills or rewards) as the true motivator. The highest scores were attributed to the support for establishing food banks and donating food surpluses (M=4.85), as well as introducing local composting programs (M=4.49), indicating that citizens are ready for the most ecologically advanced waste management models.

Table 9. Responsibility and Food Waste Management Measures

		Frequency	Percent
In your opinion, who bears the primary responsibility for food waste management?	State	373	53.9
	Everyone	319	46.1
In your opinion, which state-level measures yield the best results in waste management, particularly regarding food waste?	Vouchers and points	104	15
	Penalties	206	29.8
	Monetary compensations	303	43.8
	Discounts upon waste drop-off	79	11.4
What prevents you from sorting waste?	I always sort waste.	118	17
	I lack the necessary conditions for waste sorting at home.	151	21.8
	I am not interested in waste sorting.	112	16.2
	There are no waste sorting facilities where I live, so my efforts would be pointless.	311	45

Source: Authors' calculations

Regarding institutional responsibility, the respondents were divided between those who believe that the burden of waste and food waste management should be borne by the State (53.9%), and those who perceive that this responsibility lies with everyone (46.1%). This result highlights the respondents' expectation that shifts in environmental awareness must be driven by clear regulations and infrastructural development. Citizens demonstrate high awareness and perceive sustainable waste management as a

process requiring active synergy among all stakeholders, albeit with the State playing the primary role. When it comes to the barriers preventing proactive behavior, the study detected infrastructural pessimism; specifically, as many as 45% of the respondents emphasized that there are no conditions for waste sorting where they live. The share of citizens who are essentially uninterested in sorting waste is only 16.2%, indicating that environmental activism is not deactivated by citizen attitudes, but rather by the lack of, or distrust in, public utility logistics. Respondents prefer incentive-based economic instruments (70%) over punitive ones (29.8%), specifically: monetary compensations (43.8%) combined with a voucher system (15%) and reduced utility bills (11.4%). This finding confirms the hypothesis that a highly educated population with moderate income reacts to environmental challenges as an economic actor, favoring rewards for responsible behavior and other incentives as contributions to the household budget.

The results of the conducted linear regression analysis indicate that as much as 51.4% of the model's variance is explained by the influence of the selected factors ($R2 = 0.514$), while the high correlation coefficient value ($R=0.717$) indicates that economic stimulation, infrastructural and regulatory factors, as well as behavioral-cognitive factors, are the key drivers of habit change in food waste management. The ANOVA test results show that the model is statistically significant, $F(7, 79) = 11.973$; $p < 0.001$, leading to the conclusion that the independent variables statistically significantly predict the citizens' willingness to change their habits regarding food waste management.

Table 10. Motivational Factors for Active Citizen Participation in Waste Management

Model / Variable	Unstandardized B	Std. Error	Standardized Beta (β)	t	Sig. (p)
(Constant)	0.412	0.315	-	1.308	0.195
X1: Direct rewards (utility bill reduction)	0.345	0.118	0.312	2.923	0.004
X2: Infrastructural support (provided bin)	0.298	0.116	0.285	2.568	0.012
X3: Macroeconomic awareness (knowledge of landfill damages)	0.256	0.110	0.241	2.327	0.022
X4: Systemic incentives (vouchers and points)	0.205	0.101	0.198	2.030	0.045
X5: Penal policy (strictness of law)	0.041	0.74	0.042	0.554	0.058
X6: Circular value (knowledge of waste as a raw material)	0.025	0.98	0.023	0.255	0.079
X7: Personal economic benefit (household budget savings)	-0.018	0.85	-0.017	-0.212	0.083

Source: Authors' calculations

The analysis of individual coefficients in the regression model indicates that economic and infrastructural factors play a primary role. The largest standardized beta coefficient is observed in the Direct Reward variable ($\beta = 0.312$; $p = 0.004$). The obtained value indicates that financial reciprocity, in the form of reduced utility bills, is the strongest motivational driver for changing citizen habits. The results confirmed the existence of a

hierarchy in the order of motives, followed by infrastructural accessibility (β = 0.298), macroeconomic awareness of losses (β = 0.256), and systemic incentives such as vouchers (β = 0.205), which exert a similar but slightly weaker statistically relevant influence.

Conversely, for variables advocating external coercion—namely, the penal policy (p = 0.058) and the recognition of the circular value of waste (p = 0.079)—there is no statistically significant effect on the dependent variable. This result indicates that repression does not have a long-term effective impact; rather, individuals prefer direct benefits. Ultimately, the transformation of individual readiness should progress from passive users to active participants, driven by economic and financial incentive models along with infrastructural support.

Discussion

The research results indicate that as many as 68.8% of the respondents cite the lack of waste separation containers as the primary reason for their hesitation, i.e., inactivity. These findings align with the study by Krause et al. (2023), which emphasizes that the physical accessibility of disposal and waste separation sites is crucial, whereas their absence—combined with a lack of information—passivizes the public. The expressed high willingness to participate (e.g., 66% for collecting used oil and coffee grounds) confirms a high level of awareness and readiness to act, provided that dedicated bins are placed within neighborhoods. On the other hand, a low score was observed for composting (3.39), which does not indicate a lack of awareness but is rather a consequence of an urban lifestyle (60% of the sample resides in apartments). A viable solution could involve introducing innovative models, such as subsidies for household composters or offering shared community-based utility solutions.

A significant number of respondents (over 91% are open to composting given an incentive) suggest that lower utility bills, vouchers, and/or points would help address the food waste issue. This thesis is consistent with the views of Thaler and Sunstein (2008) regarding the impact of the nudge theory, stating that financial incentives (vouchers and points) yield greater results than punitive measures. While some authors have highlighted the positive role of strict enforcement measures (Qasim et al., 2020) or, conversely, the limited impact of repression (Al Habsi et al., 2026), the results of this study demonstrate that penalties “do not work” in Serbia. This points to the need for developing an alternative approach to waste disposal management, rather than relying solely on inspection supervision.

The high willingness of citizens to donate surplus food (M=4.75) and engage in composting (M=4.28) indicates a significant potential for reducing food supply chain losses and diverting bio-waste into organic agricultural production, as confirmed by the study of Berjan et al. (2022) on specific motives in Serbia.

The fact remains that 51.3% of the respondents perceive the State as the primary bearer of responsibility, while 46.1% display high awareness on this matter and emphasize the necessity of collective action. The solution lies in enhancing the institutional framework,

where collaborative efforts—specifically through the targeted involvement of SMEs—would educate users, offer tangible benefits, and ultimately transform citizens from passive consumers into "prosumers" (producers-consumers of raw materials).

The study established a high, statistically significant impact of direct rewards and financial reciprocities on citizen readiness, which aligns with the conclusions of Fullerton and Kinnaman (1999) regarding economic instruments. Vouchers and points act as positive motivators, consistent with the research by Kosters & Van der Heijden (2015), Thaler and Sunstein (2008) on subtle incentives (nudges), and Omar & Rohani (2015). Although Zadik and Katz (2025) emphasize the importance of incentives for the transition, the research results (for Serbia) indicate that utility bill reductions are more effective than any potential benefits, meaning that citizens in Serbia respond to direct price incentives, which creates opportunities for designing sustainable economic models within the circular agroeconomy (Đorić, 2022).

A good infrastructure, treated as a convenience in waste disposal, has a highly statistically significant impact, which aligns with the views of Krause et al. (2023). High environmental awareness among citizens, in the absence of convenience, is not a sufficient driver, which amplifies the importance of the technical aspects of waste management (Vukadinović, 2018; Svensson & Karlsson, 2024). A comprehension of the broader macro-aspect of waste disposal is present among the respondents, and the study established its statistically significant impact, as confirmed by Schanes et al. (2018). High consensus was reached with the stance of Berjan et al. (2022) regarding the specific sensitivity of citizens toward food chain losses; thus, the existence of internal pressure among respondents due to awareness of state-level losses (landfills, resources) was proven.

Although Rai et al. (2025) emphasize the importance of understanding waste as a resource, the conducted research demonstrates that knowledge alone is not a sufficient motivator. In practice, there is a prominent knowledge-action gap (Thøgersen, 2003); knowledge remains largely passive, which is consistent with the findings of Matzembacher et al. (2020). Respondents are not sufficiently prepared to conserve food, resulting in significant quantities being wasted; thus, household savings alone do not provide a sufficient motive to alter habits or to foster a readiness to separate and collect food waste (Prelez et al., 2023). These conclusions underscore the necessity of identifying new models to stimulate citizens to transform their awareness regarding food waste disposal.

Conclusion

The essence of the Green Agenda for the Western Balkans in the context of food bio-fraction management rests upon the obligation to harmonize the national legislations of the region's countries with the European Union acquis, aiming for a complete transition from a linear to a circular economic model. Accordingly, the Western Balkan states have committed to transposing the provisions of the EU Waste Framework Directive

into their national legal frameworks governing waste matter. In 2025, Serbia adopted a new Waste Management Law, the key objectives of which are deeper alignment with EU directives, system digitalization, and the strengthening of inspection supervision. Nevertheless, it is evident that the new Waste Management Law is not fully harmonized with European Union standards. Many provisions of this new law, which serves as the lex generalis in waste management matter, require precise secondary legislation (decrees and rulebooks) to properly define and regulate this field.

The research results point to obstacles in food waste separation, with 68.8% of respondents citing the lack of specialized containers as a key factor. The high readiness to act (66% for collecting oil and coffee) indicates a latent motivation, conditional upon accessibility, while the low score for composting (M=3.39) stems from urban living conditions (60% of respondents reside in apartments), suggesting a need for subsidized household systems or shared community utility options. Over 91% support financial rewards such as lower bills or vouchers, in line with nudge principles that favor incentives over penalties, as enforcement demonstrates limited effectiveness in the domestic context.

High scores for food donation (M=4.75) and food banks (M=4.28) signal solidarity, confirmed by regional studies on motivations within the Western Balkans. The State is viewed as the primary bearer of responsibility (51.3%), yet there is strong backing for collective engagement (46.1%), highlighting the role of SMEs in education and the transformation of citizens into active prosumers. Financial reciprocity and rewards carry a statistically significant impact, countering passivity despite an awareness of macroeconomic costs, where infrastructure transcends pure knowledge as a driver.

Based on empirically confirmed hypotheses and identified barriers in food waste management, the following set of targeted measures, tailored to urban living conditions, is proposed:

The creation of an “Incentivized Recycling” model should introduce direct financial incentives through personalized access cards for smart containers. These would log the submitted food bio-fraction and automatically reduce the monthly utility bill or generate shopping vouchers redeemable with partners within the small and medium enterprise (SME) sector.

Due to living conditions in urban environments, infrastructural adaptation is required; solutions must be technically feasible within constrained spaces. The subsidized procurement of small household composters is proposed, alongside the placement of dedicated containers for used oil and coffee grounds in the immediate vicinity of residential buildings (within a 50–100 meters radius).

The lack of citizen awareness can be overcome through cooperation with the private sector. It is necessary to develop mobile applications that display container locations in real-time, while simultaneously providing education on proper waste separation and individual resource savings (e.g., reducing CO2 and methane emissions). Educational

campaigns should be rebranded to place the focus on concrete macroeconomic losses rather than abstract messages about a "clean planet."

The expressed willingness to donate food requires a legally and logistically defined process. Tax incentives are proposed for retail chains and SMEs that donate surplus food near its expiration date to food banks, accompanied by the construction of a logistical network for rapid distribution.

The proposed measures, grounded in the research findings, enable the transformation of passive awareness into active waste management. Implementation requires coordination between local authorities, the private sector, and citizens, with effects measured through indicators such as separation rates and waste reduction, thereby achieving sustainable economic and environmental progress while establishing a stable and circular agri-food system in line with the principles of the Green Agenda.

Conflict of interests

The authors declare no conflict of interest.

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EVALUATION OF DIGITAL TWIN ARCHITECTURES FOR PRECISION AGRICULTURE USING MULTI-CRITERIA DECISION ANALYSIS

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ABSTRACT

This paper selected the most suitable digital twin for precision agriculture to enable more precise and rational irrigation on a farm. Six alternatives were evaluated using assessments by seven experts in the field and ten predefined technological, economic and environmental criteria. For this purpose, fuzzy logic in multi-criteria decision-making was applied, specifically the fuzzy Simple Weight Calculation (SiWeC) method to determine criterion weights and the fuzzy Ranking of Alternatives with Weights of Criterion (RAWEC) method for the final ranking of alternatives. The results show that the experts attach the greatest importance to readiness for artificial intelligence integration (AI readiness) and ease of implementation, while the integrated architecture is the most suitable among the alternatives analysed. Its continued application is recommended, subject to a prior assessment of farms' investment capacity and digital readiness.

Introduction

Today, digital transformation can be considered one of the key directions of development in modern agroeconomic systems, particularly given the growing demands for increased productivity, production sustainability and optimisation of existing resources (Wolfert et al., 2017; Klerkx et al., 2019).

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Models involving traditional agriculture face numerous limitations due to climate change, natural resource degradation, input price volatility and the need for more efficient use of water, energy and labour (Gebbers & Adamchuk, 2010). In view of this, precision agriculture is becoming central to the development of the agricultural sector, integrating the Internet of Things (IoT), sensor networks, satellite monitoring, artificial intelligence (AI), machine learning and big data analytics (Liakos et al., 2018; Khanna & Kaur, 2019).

As Tao et al. (2019) state, one of the most advanced concepts in modern digital agriculture is the Digital Twin, defined as a digital replica of a physical system that enables continuous monitoring, simulation, prediction and optimisation of agricultural processes in real time.

Furthermore, Digital Twin architectures enable the effective integration of data from various sources (soil sensors, weather stations, drones, satellites, machinery and farm management information systems), thereby improving the management of production processes, particularly in precision irrigation, input management, yield prediction and resource optimisation (Verdouw et al., 2021). This contributes to a significant increase in productivity, lower costs and improved sustainability, which in turn aligns with the development of the Agriculture 4.0 and Agriculture 5.0 concepts (Saiz-Rubio & Rovira-Más, 2020).

Moreover, selecting the optimal digital twin architecture remains a complex multi-criteria problem. Different architectures, including cloud-based, edge-based, hybrid, AI-driven autonomous, blockchain-integrated and IoT-CPS models, differ according to various criteria (Ferrag et al., 2020). This requires a systematic approach to decision-making that simultaneously encompasses economic, technological, operational, sustainability and other dimensions.

In real-world conditions, the evaluation of DT architectures often relies on expert judgements expressed as linguistic assessments, with subjectivity, imprecision and uncertainty posing significant methodological challenges. Conventional decision-making methods are often insufficient for adequately modelling such conditions, making fuzzy logic one of the most suitable solutions (Zadeh, 1965). Integrating fuzzy approaches with multi-criteria decision-making (MCDM) methods enables more precise modelling of uncertainty and more reliable decision-making in complex systems (Bellman & Zadeh, 1970).

A particularly significant approach in this study is the integration of the fuzzy SIWEC and fuzzy RAWEC methods. Combining these methods provides an integrated framework that enables both the prioritisation of criteria and the ranking of Digital Twin alternatives with a high level of methodological robustness.

Although numerous studies on Digital Twin technologies and individual MCDM methods have been conducted, a research gap remains in the literature regarding the application of an integrated fuzzy multi-criteria approach to evaluating Digital Twin architectures in precision agriculture. Previous research has mainly focused on technical or individual

economic aspects of digitalisation, while an interdisciplinary framework linking technological performance, agroeconomic sustainability, AI readiness and resource efficiency within a single decision-making model is lacking (Verdouw et al., 2021).

Accordingly, the subject of this research would be the evaluation and selection of the optimal Digital Twin architecture for precision agriculture using an integrated fuzzy SIWEC-fuzzy RAWEC model, while the objective would be to identify the architecture that provides the best balance among the existing criteria.

The scientific contribution would be based on the development of an innovative methodological framework for evaluating digital architectures in agriculture, practical support for decision-makers in selecting optimal technological solutions, and a strategic contribution to understanding the digital transition of agriculture. The research thus links agroeconomics, digitalisation, AI and multi-criteria decision-making within a single interdisciplinary model with significant theoretical and practical implications.

In addition, the following research questions arise, which the study should address:

- Which Digital Twin system architecture is the most suitable solution for precision agriculture based on the predefined criteria?
- Which criteria have the greatest influence on selecting the optimal Digital Twin system architecture in modern agricultural systems?
- Does the application of fuzzy MCDM methods enable more reliable evaluation of Digital Twin architectures under conditions of uncertainty and expert subjectivity?

Literature review

Recent research confirms that the Digital Twin system in agriculture is no longer merely a conceptual framework but is becoming a practical technological platform based on IoT sensors, UAV systems, satellite imagery, artificial intelligence, machine learning and cloud/edge infrastructure. Peladarinos et al. (2023) provide a comprehensive review of digital twin applications in smart agriculture and emphasise their importance for more precise decision-making, automation and sustainable resource management. Zhang et al. (2025) also state that Digital Twin technology in agriculture has considerable potential to increase productivity, sustainability and decision-making quality, but that challenges relating to standardisation, interoperability, architectural layers and practical implementation remain unresolved.

Subeesh and Chauhan (2025) view the Agricultural Digital Twin as an advanced form of smart farming system that combines cyber-physical systems, IoT devices, sensors and data on soil, crops, weather conditions and equipment. Their work indicates that data quality, the integration of heterogeneous sources, scalability, costs and the application of systems on real farms remain key problems.

Awais et al. (2025) further emphasise that precision agriculture based on Digital Twin technology requires the integration of IoT, UAV technologies and AI analytics.

Their systematic review covers 167 studies from 2018–2025 and shows that a clearer framework is needed for the design, integration and optimisation of Digital Twin systems in a smart farming environment.

Kim et al. (2024) provide an empirical contribution to the literature by developing an agricultural digital twin for mandarin production. This study shows that it can be used to simulate, monitor and predict actual production processes, confirming that digital twins can have practical value in agronomic and managerial decision-making.

From the perspective of architecture evaluation, it is particularly important that these systems are not uniform. They may differ in their level of data integration, type of sensor infrastructure, data processing approach, degree of AI automation, level of interoperability, costs and sustainability. Therefore, evaluating these architectures naturally falls within multi-criteria decision-making, since selecting the optimal architecture cannot be based on a single indicator alone.

In recent years, multi-criteria methods have increasingly been used in digital and precision agriculture. Kizielewicz et al. (2025), for example, develop an MCDM/MCDA framework for selecting UAV sensors in precision agriculture, using objective weighting methods such as Standard Deviation, Entropy, CRITIC and MEREC. This study is methodologically significant because it demonstrates that selecting digital components in precision agriculture is a multi-criteria problem.

Similarly, Puška et al. (2025) apply an MCDM approach to evaluate mobile applications for small farms. Their study shows that digital solutions in agriculture can be ranked according to functionality, costs, availability, user accessibility and practical value for farmers. In addition to the above, other recent studies and application reviews report the successful use of digital twin systems in agriculture and agribusiness, supporting their increasing adoption (Escribà-Gelonch et al., 2024; Tagarakis et al., 2024; Peladarinos et al., 2024; Gund et al., 2025).

A review of the remaining existing literature reveals a clear research gap: although numerous papers address Digital Twin technology in agriculture and an increasing number address the application of MCDM methods in digital agriculture, few directly integrate these two strands by evaluating alternative DT architectures for precision agriculture. This is precisely why the topic of this study has scientific potential.

Research methodology

The research was conducted in the following five phases:

- Phase 1. Defining the research objective,
- Phase 2. Selecting criteria and alternatives,
- Phase 3. Selecting appropriate experts,
- Phase 4. Processing data using MCDM methods,
- Phase 5. Conducting sensitivity analysis.

The research objective was defined in the preceding introductory section, while the criteria and alternatives were selected through an analysis of scientific and professional literature and additional consultations with the experts selected for this study. The selection was narrowed down to ten technical, economic and environmental criteria, whose names, brief descriptions and types are presented in Table 1 below.

Table 1. Criteria used

Criterion	Criterion name	Criterion description	Type
C1	Cost	Total costs of DT system implementation, infrastructure, maintenance and upgrades	Cost
C2	Interoperability	The system's ability to communicate with IoT devices, sensors, ERP/FMIS platforms and other technologies	Benefit
C3	Scalability	The possibility of expanding the system to include more plots, sensors, users and processes	Benefit
C4	Real-time capability	Speed of data collection, processing and response in real time	Benefit
C5	Cybersecurity	Level of protection of data, infrastructure and communication channels	Benefit
C6	Sustainability	Contribution to sustainable resource use, waste reduction and ecological balance	Benefit
C7	Ease of implementation	Ease of implementation, expertise required and setup time	Benefit
C8	ROI	Expected return on investment through increased productivity and reduced costs	Benefit
C9	AI readiness	System readiness for integrating AI/ML models and advanced analytics	Benefit
C10	Resource efficiency	Efficiency in the use of water, energy, pesticides, fertilisers and labour	Benefit

Source: Authors

The importance of individual criteria has also been described in previous scientific studies, with an overview and their application presented in Table 2 below.

Table 2. Overview of the previous use of the criteria

Criterion	Criterion name	Recommended source	Application in criterion selection
C1	Cost	Klerkx, L., Jakku, E., & Labarthe, P. (2019)	Costs of digital agriculture adoption, investment barriers
C2	Interoperability	Wolfert, S., Ge, L., Verdouw, C., & Bogaardt, M. J. (2017)	Integration of IoT, FMIS and Big Data
C3	Scalability	Tao, F., Zhang, H., Liu, A., & Nee, A. Y. C. (2019)	Scalability of Digital Twin systems
C4	Real-time capability	Khanna, A., & Kaur, S. (2019)	Real-time monitoring and decision-making
C5	Cybersecurity	Ferrag, M. A., Maglaras, L., & Derhab, A. (2020)	Cybersecurity in IoT and smart farming
C6	Sustainability	Kamilaris, A., Kartakoullis, A., & Prenafeta-Boldú, F. X. (2017)	Sustainable digital agriculture

Criterion	Criterion name	Recommended source	Application in criterion selection
C7	Ease of implementation	Rogers, E. M. (2003)	Adoption and implementation of innovations
C8	ROI	Lowenberg-DeBoer, J., & Erickson, B. (2019)	Profitability of precision agriculture technologies
C9	AI readiness	Liakos, K. G., et al. (2018)	AI/ML readiness of the system
C10	Resource efficiency	Gebbers, R., & Adamchuk, V. I. (2010)	Resource optimisation through precision agriculture

Source: Authors

An overview and description of the proposed alternatives are presented in Table 3. These are Digital Twin system architectures currently available on the market and increasingly used for irrigation and the management of production processes on a farm.

Table 3. Alternatives used

Alternative	Architecture name	Brief description
A1	Cloud-based Digital Twin	Centralised DT architecture based on cloud platforms for data storage, processing and analysis
A2	Edge-based Digital Twin	Local data processing through edge devices and gateway systems
A3	Hybrid Digital Twin	A combination of cloud and edge approaches to balance local speed and centralised analytics
A4	AI-driven Autonomous DT	A DT system with integrated AI/ML models for autonomous decision-making
A5	Blockchain-integrated DT	DT architecture with a blockchain layer for security and traceability
A6	IoT-CPS Integrated DT	A fully integrated DT with IoT networks and cyber-physical systems

Source: Authors

Expert selection is an integral part of the research, and the opinions of seven experts were used for this study. The composition of the expert panel took into account their experience in the field, the institutions from which they came, their availability and their ability to provide prompt and reliable opinions (assessments) within the study. Faculty members from the Faculties of Agriculture in Belgrade and Novi Sad and researchers from national scientific institutes whose research activities are partly based on the topic analysed in this study were engaged. They had previously received a questionnaire designed by the authors, in which they provided their expert assessments.

The required calculations were based on the application of multi-criteria methods, specifically their fuzzy variants. The SIWEC (*Simple Weight Calculation*) method was selected to determine the relative importance of the criteria. The choice of this method is justified by the need to incorporate expert knowledge and preferences into criterion weighting through a transparent and cognitively less demanding procedure. Unlike subjective methods based on pairwise comparisons or prior ranking of criteria, SIWEC allows experts to directly assess the importance of each criterion. This procedure

reduces the number of assessments required, facilitates the inclusion of more criteria and simplifies group decision-making. An additional advantage of the method is the possibility of assigning different levels of importance to experts according to their experience, expertise and knowledge of the research problem. Individual assessments are used to form aggregated and normalised weights that express the relative importance of the criteria in the decision-making context under consideration (Puška et al., 2024).

The most important contributions of the SIWEC method are its ease of application, flexibility (through combination with other methods), potential for fuzzy extension, suitability for a large number of criteria, transparency, lower cognitive burden on decision-makers (experts) and previous successful practical application. In this study, we used the fuzzy variant of this method, whose steps are presented below:

Step 1. Assessing the criteria using linguistic values.

Step 2. Transforming linguistic values into fuzzy numbers.

Step 3. Normalising fuzzy numbers.

$$\tilde{n}_{ij} = \frac{x_{ij}^{l}}{max\ x_{ij}^{u}}, \frac{x_{ij}^{m}}{max\ x_{ij}^{u}}, \frac{x_{ij}^{u}}{max\ x_{ij}^{u}}$$

Where $max\ x_{ij}^{u}$ is the maximum value of the fuzzy number.

Step 4. Calculating the standard deviation ($st.dev_j$).

Step 5. Weighting the normalised values.

$$\tilde{v}_{ij} = \tilde{n}_{ij} \times st.dev_j$$

Step 6. Calculating the sum of weights.

$$\tilde{s}_j = \sum_{j=1}^{n} \tilde{v}_j$$

Step 7. Determining criterion weights.

$$\tilde{w}_j = \frac{s_j^{l}}{\sum_{j=1}^{n} s_j^{u}}, \frac{s_j^{m}}{\sum_{j=1}^{n} s_j^{m}}, \frac{s_j^{u}}{\sum_{j=1}^{n} s_j^{l}}$$

For the final ranking of the alternatives analysed, we used the fuzzy *Ranking of Alternatives with Weights of Criterion* (RAWEC) method. The innovative fuzzy Ranking of Alternatives with Weights of Criterion (RAWEC) method was used to rank the predefined cultivars. The RAWEC method was developed by Puška et al. (2024a), and its steps are as follows:

Step 1. Formation of the decision matrix.

Step 2. Normalization of the decision matrix

$$n_{ij} = \frac{x_{ij}^{l}}{\max x_{j}^{u}}, \frac{x_{ij}^{m}}{\max x_{j}^{u}}, \frac{x_{ij}^{u}}{\max x_{j}^{u}}; \; n'_{ij} = \frac{\min x_{j}^{l}}{x_{ij}^{u}}, \frac{\min x_{j}^{l}}{x_{ij}^{m}}, \frac{\min x_{j}^{l}}{x_{ij}^{l}}; \text{ for benefit criteria}$$

$$n_{ij} = \frac{\min x_{j}^{l}}{x_{ij}^{u}}, \frac{\min x_{j}^{l}}{x_{ij}^{m}}, \frac{\min x_{j}^{l}}{x_{ij}^{l}}; \; n'_{ij} = \frac{x_{ij}^{l}}{\max x_{j}^{u}}, \frac{x_{ij}^{m}}{\max x_{j}^{u}}, \frac{x_{ij}^{u}}{\max x_{j}^{u}}; \text{ for cost criteria}$$

Where, $x_{j\,min}$ is the minimum value of individual criterion, and $x_{j\,max}$ is the maximum value of individual criterion.

Step 3. Calculating the deviation from the criterion weight

$$\tilde{v}_{ij} = \sum_{i=1}^{n} \tilde{w}_j \cdot \left(1 - \tilde{n}_{ij}\right); \tilde{v}'_{ij} = \sum_{i=1}^{n} \tilde{w}_j \cdot \left(1 - \tilde{n}'_{ij}\right)$$

Where, $\tilde{w}_j$ is the criterion weight

Step 4. Defuzzification

$$v_{ij\,def} = \frac{v_i^{l} + 4v_i^{m} + v_i^{u}}{6}; v'_{ij\,def} = \frac{v_i^{l} + 4v_i^{m} + v_i^{u}}{6}$$

Step 5. Calculating the value of the RAWEC method

$$Q_i = \frac{v'_{ij} - v_{ij}}{v'_{ij} + v_{ij}}$$

For the application of these methods, that is, for the calculations themselves, the fuzzy scale presented in Table 4 below was used. The scale shows linguistic values converted into numbers.

Table 4. Fuzzy assessment scale

1	Very low	VL	(1,1,2)
2	Low	L	(1,2,4)
3	Medium Low	ML	(2,4,6)
4	Medium	M	(3,5,7)
5	Medium Good	MG	(5,7,9)
6	Good	G	(7,9,10)
7	Very good	VG	(9,10,10)

Source: Puška et al., 2024

Results and discussion

The study analyses the selection of a digital twin architecture to improve precision irrigation and resource management on a medium-sized farm. The subject of the analysis is the architectural option for a Digital Twin system. The user context involves a farm considering the integration of data on soil moisture, weather conditions and irrigation

system operation with a digital model for condition monitoring and decision support. The six alternatives in Table 3 above are compared according to the ten predefined criteria.

The first step is to construct the initial decision matrix using linguistic values obtained from expert assessments for each predefined criterion (Table 5).

Table 5. Initial decision matrix for the criteria

Expert/ Criteria	C1	C2	C3	C4	C5	C6	C7	C8	C9	C10
E1	VG	G	G	G	MG	M	G	ML	VG	ML
E2	G	G	VG	MG	M	ML	MG	L	G	M
E3	G	G	M	G	VG	L	G	G	VG	M
E4	MG	MG	G	G	MG	ML	VG	MG	VG	ML
E5	G	G	G	MG	MG	L	VG	M	VG	ML
E6	G	MG	G	G	MG	ML	G	ML	G	ML
E7	MG	G	G	VG	MG	L	VG	ML	VG	ML

Source: Authors, based on the expert survey

Following the subsequent steps of the selected method, the research results show that "AI readiness" (C9; 0.1318) and "Ease of implementation" (C7; 0.1244) have the greatest relative importance in selecting digital twin architectures for precision agriculture. This pattern of weights can be interpreted as an effort by experts to combine advanced analytical capabilities with the practical feasibility of introducing the technology (Table 6). Similar findings are reported by Purcell and Neubaue**r** (2023), who identify these functions as a basis for improving decision support and automation in agriculture. This in itself indicates the importance of future system upgrades, but does not confirm the quality of its predictions or its economic viability.

Table 6. Ranking of criteria

ID	Criterion	Type	$\tilde{w}_j$
C1	Cost	Cost	0.1171
C2	Interoperability	Benefit	0.1151
C3	Scalability	Benefit	0.1164
C4	Real-time capability	Benefit	0.1171
C5	Cybersecurity	Benefit	0.0997
C6	Sustainability	Benefit	0.0482
C7	Ease of implementation	Benefit	0.1244
C8	ROI	Benefit	0.0702
C9	AI readiness	Benefit	0.1318
C10	Resource efficiency	Benefit	0.0602

Source: Authors' calculations

The high assessment of the criterion relating to ease of implementation indicates that technological sophistication represents only one part of the decision to select a digital solution. This can be linked to the study by Klerkx et al. (2019), which considers the adoption of digital technologies in terms of farmers' skills, changes in work, knowledge systems and institutional relationships. All of this points to the need to adapt Digital Twin systems to the competencies available to users and the organisation of production. The practical implication is that the development of advanced functionalities should be accompanied by training, advisory support and clear operating procedures.

In addition, the cost and real-time capability criteria have equal weights (0.1171), while scalability (0.1164) and interoperability (0.1151) are assessed as almost equally important. In line with the above, Verdouw et al. (2021) emphasise that digital twins enable the management of agricultural processes based on data available in near real time and the simulation of the consequences of interventions. The results of this paper complement this understanding by showing that, alongside system functionality, experts attach importance to costs and the possibility of system integration and expansion.

Table 7. Initial decision matrix for the alternatives

Expert I										
	C1	**C2**	**C3**	**C4**	**C5**	**C6**	**C7**	**C8**	**C9**	**C10**
A1	ML	MG	MG	M	MG	G	MG	G	VG	G
A2	ML	G	G	ML	ML	MG	MG	M	MG	MG
A3	MG	G	G	MG	MG	MG	M	G	G	VG
A4	MG	MG	G	MG	MG	G	MG	MG	G	G
A5	M	M	MG	MG	MG	MG	M	MG	MG	MG
A6	L	G	G	VG	G	VG	G	G	VG	MG
					. . .					
Expert VII										
	C1	C2	C3	C4	C5	C6	C7	C8	C9	C10
A1	M	MG	MG	M	MG	G	MG	G	M	MG
A2	ML	G	MG	M	ML	MG	MG	M	G	MG
A3	MG	M	M	MG	M	MG	M	M	VG	VG
A4	MG	MG	G	VG	MG	G	MG	MG	G	G
A5	M	M	VG	MG	MG	G	M	MG	MG	VG
A6	ML	G	VG	MG	G	G	M	G	G	VG

Source: Authors, based on the expert survey

The highest-ranked alternative is the architecture integrating the Internet of Things and cyber-physical systems (IoT-CPS Integrated DT-A6), with a Q_i value of 0.9541 (Table 7). In line with this result, Peladarinos et al. (2023) point out that integrating different data sources enables more comprehensive monitoring of production conditions and supports decisions on irrigation, fertilisation and crop protection. In this sense, the ranking of alternative A6 is consistent with the importance of integration emphasised in the literature.

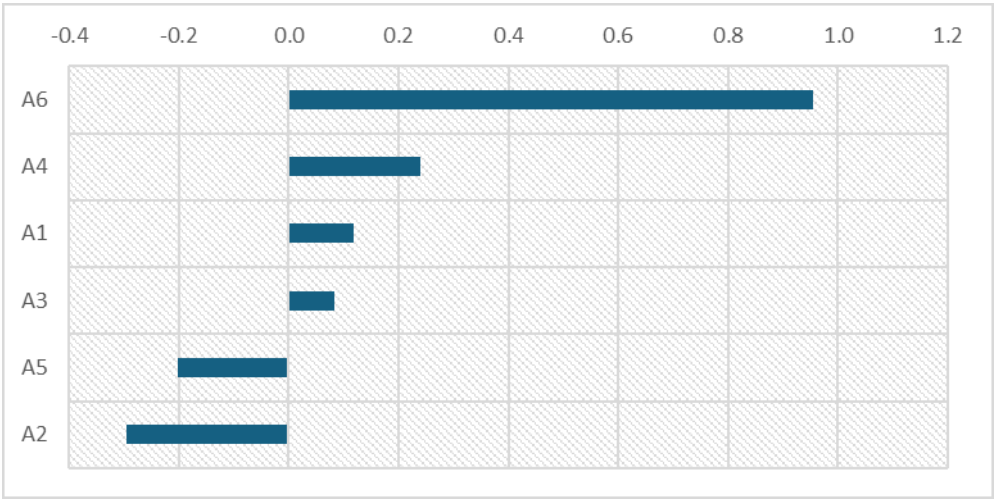
Table 8. Final ranking of alternatives

ID	Alternative	v_{ij}	v'_{ij}	Q_i	Rank
A6	IoT-CPS Integrated DT	0.0089	0.3769	0.9541	1
A4	AI-driven Autonomous DT	0.1581	0.2578	0.2397	2
A1	Cloud-based Digital Twin	0.1853	0.2348	0.1177	3
A3	Hybrid Digital Twin	0.1896	0.2237	0.0824	4
A5	Blockchain-integrated DT	0.2500	0.1663	-0.2011	5
A2	Edge-based Digital Twin	0.2584	0.1404	-0.2958	6

Source: Authors' calculations

The second-place ranking of the AI-driven autonomous architecture (A4; $Q_i = 0.2397$) shows that the high importance of AI readiness is insufficient for this alternative to achieve the best overall ranking. Within the model applied, the combination of all criteria favours alternative A6. Cloud-based architectures rank third (A1; $Q_i = 0.1177$), while hybrid architectures rank fourth (A3; $Q_i = 0.0824$). These should be considered further because of the relatively small difference between their scores (Table 7). Figure 1 below provides a visualisation of the final ranking of alternatives.

Figure 1. Ranking using the fuzzy RAWEC method



Conclusion

This study considers the selection of the most suitable digital twin architecture for precision agriculture. An integrated fuzzy SIWEC-fuzzy RAWEC model was used in the study. The objective was to connect technology, economics and ecology within a single decision-making framework. Six alternatives were evaluated in the analysis. The assessment was based on ten criteria. The opinions of seven experts were used for the assessment. All experts provided their assessments. This enabled multiple aspects to be linked within a single system. The results show that the most important factors are the capacity to integrate artificial intelligence and ease of implementation. This means that experts favour architectures that can readily adapt to new technologies. Architectures that are easily introduced into practice also have an advantage. Costs also have a major influence. Real-time capability is crucial. Scalability and interoperability are also important. This indicates that technology must adapt its performance to the actual needs of users. The lower weights of sustainability and resource efficiency do not mean that these criteria are unimportant. They simply show that the expert panel placed greater emphasis on other aspects.

What could be characterised as the methodological contribution of the paper is the successful application of an integrated multi-criteria modelling framework, while its practical usefulness would lie in supporting agricultural producers, advisory services and investors when considering the introduction of digital solutions. Future research should expand the expert decision-making panel and its composition, and focus on comparing the results with similar ranking methods and validating the approach on farms of different sizes and with different investment and digital capacities.

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Conflict of interests

The authors declare no conflict of interest.

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HALAL COMPETENCIES OF EMPLOYEES IN THE AGRI-FOOD INDUSTRY: PERCEIVED IMPORTANCE, DETERMINANTS AND ASSOCIATION WITH ORGANISATIONAL EFFICIENCY

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ABSTRACT

This study explores how employees assess the importance of 17 halal competencies, how these competencies are structured, and how they relate to organisational efficiency. It draws on responses from 225 employees in 79 halal-certified companies across Bosnia and Herzegovina, Serbia and Croatia; 92% operate in the agri-food sector. Competency ranking, principal component analysis, non-parametric tests and hierarchical regression identified two dimensions: value-normative and technical-behavioural. Employees placed the greatest importance on hygiene requirements and distinguishing between halal, haram and mashbooh, while participation in professional development ranked lowest. Halal team members and quality staff rated competencies more highly than owners and managers. After controlling for employee characteristics, the halal competency index explained additional variation in organisational efficiency. Only the technical-behavioural dimension emerged as an independent predictor, suggesting that training should focus on the practical knowledge, skills and everyday work habits employees need to fulfil their halal-related responsibilities.

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This paper draws on data collected for a master's thesis defended at the Faculty of Economics, University of Tuzla, in 2025. Findings from the same research relating to the validation of the KSAH framework were previously published in the Proceedings of the 9th International Scientific Conference "Economy of Integration" – ICEI 2025 (Umihanić & Sakić, 2025). The present paper reports new analyses that were not included in that publication.

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Introduction

The halal market is one of the fastest-growing segments of the global food industry, serving approximately two billion Muslim consumers (Dinar Standard, 2024). In Islamic dietary principles, *halal* refers to what is permissible, *haram* to what is prohibited, and *mashbooh* to what is doubtful or of uncertain status. For agri-food companies in Southeast Europe, halal certification provides access to international halal markets and enables product differentiation. Approximately 250 companies in Bosnia and Herzegovina, Serbia, and Croatia are halal-certified, mainly in the meat, dairy, bakery, oil, and milling sectors, under BAS 1049, a standard harmonised with OIC/SMIIC standards (Agencija za certificiranje halal kvalitete, n.d.).

Halal production requires preserving product integrity throughout the value chain, from raw materials to the final consumer (Ali et al., 2017; Khan et al., 2018). This involves a preventive, process-oriented approach based on monitoring, risk identification, and preventive and corrective measures. Employees play a key role through their understanding of halal requirements, consistent application of procedures, and commitment to the values underlying the halal system (Talib et al., 2015). Halal standards BAS 1049:2023 (BAS, 2023) and OIC/SMIIC 18:2021 (OIC/SMIIC, 2021) require competent and appropriately trained personnel but do not specify a detailed list of competencies or their assessment methods. This raises two research questions: which knowledge, skills, attitudes, and habits constitute employees' halal competencies, and how are they associated with halal system efficiency?

Research on the human factor in the halal industry has mainly been conducted in Southeast Asia, focusing on employee training needs (Hashim & Shariff, 2016; Jamaludin et al., 2015), the role of human capital in obtaining halal certification (Rafiki & Abdul Wahab, 2016), and factors affecting halal companies' organisational performance (Bidin et al., 2021; Othman et al., 2019).

Recent studies have proposed competency models for halal executives (Rosli et al., 2022) and halal supply chain personnel (Voak et al., 2023). However, research on employee competencies in the halal industry in Europe remains limited, particularly in Southeast European countries. Sakić (2025) developed and operationalised a framework of 17 halal competencies based on the KSAH/KASH approach (knowledge, skills, attitudes, and habits) and the requirements of halal standards. The framework was examined as part of a broader study on human resource management in the halal industry in Bosnia and Herzegovina, Serbia, and Croatia. Data collected in that research were also used in this study.

Using this framework, Umihanić and Sakić (2025) examined the relationships between the four KSAH dimensions and organisational efficiency. The results indicated high internal consistency of the measurement scales and strong intercorrelations among the four competency dimensions. Regression analysis identified skills as a statistically significant independent predictor of internal halal audit and habits as a significant predictor of customer satisfaction.

This study continues previous research and methodologically extends the analysis of halal competencies. Instead of examining them through the four composite KSAH dimensions, it analyses the perceived importance and empirical grouping of all 17 halal competencies. It also examines differences by halal team membership, participation in halal training, job position, and educational level. Hierarchical regression assesses the contribution of halal competencies to organisational efficiency while controlling for relevant employee characteristics.

Theoretical Framework and Hypotheses

The concept of competencies has developed through different approaches aimed at explaining why some employees achieve better results than others. McClelland (1973) emphasised the importance of assessing competencies through job-related behaviours, while Boyatzis (1982) focused on individual characteristics contributing to effective performance. Spencer and Spencer (1993) distinguished visible competencies, such as knowledge and skills, from less visible components, including motives, traits, and values. From the resource-based view (RBV), organisation-specific competencies can provide sustained competitive advantage (Lado & Wilson, 1994). More recent approaches also recognise behavioural competencies alongside knowledge and skills (Armstrong & Taylor, 2023).

The widely used KSA and KSAO models describe competencies through knowledge, skills, abilities, and other personal characteristics (Rehmani et al., 2020; Society for Human Resource Management, 2022). However, these models do not fully capture the value-related aspects of halal competencies, which include attitudes, behavioural patterns, and alignment with Islamic values alongside professional knowledge and operational skills. Employees must therefore understand the distinction between halal, haram, and doubtful (mashbooh) status, apply procedures for handling raw materials and halal critical control points (HrCCP), and take personal responsibility for preserving product integrity (Jašić et al., 2022).

In addition to general professional competencies, research by Abu Bakar et al. (2016) highlights the role of religiosity in work engagement. Rafiki and Abdul Wahab (2016) found that employees' experience, motivation, training, and education in the halal industry increase the likelihood of obtaining halal certification, while Voak and Fairman (2020) emphasise knowledge of halal regulations and standards as essential for competent work.

The relationship between employee competencies and organisational efficiency can also be examined through high-performance work systems (HPWS) and quality management. Rehmani et al. (2020) examined HPWS practices covering employee knowledge, skills, abilities, motivation, and opportunities to contribute, alongside quality management practices. They found a statistically significant positive relationship between HPWS practices and organisational effectiveness.

With the aim of proposing a unified model of employee competencies in the halal industry, Sakić (2025) developed a matrix of 17 halal competencies organised into four categories: knowledge, skills, attitudes, and habits, as defined by the KSAH/KASH approach (The Peak Performance Center, 2025). This halal competency model reflects halal standard requirements and the importance of employees' responsibility for their consistent and effective implementation.

Using this competency model, Umihanić and Sakić (2025) found high internal consistency and strong intercorrelations among the four KSAH dimensions. Their associations with organisational efficiency were positive, statistically significant but relatively weak (r = 0.25–0.37), while only some dimensions made an independent statistically significant contribution in the regression models.

These findings provide a basis for further examining the 17 individual halal competencies, their perceived importance, and their relationship with organisational efficiency. On this basis, the following hypotheses were formulated:

H1: Employees who are members of a formal halal team and those who have attended halal training assign greater importance to halal competencies than other employees.

H2: The perceived importance of halal competencies differs according to employees' job positions and educational levels.

H3: The perceived importance of halal competencies is positively associated with the dimensions of organisational efficiency of the halal system, even after controlling for employee characteristics.

Materials and Methods

Employees' halal competencies and their association with organisational efficiency were examined using a quantitative cross-sectional design. The study population comprised 248 halal-certified companies in Bosnia and Herzegovina (115), Serbia (40), and Croatia (93), identified through the registers of the Agency for Halal Quality Certification and the Centre for Halal Quality Certification. Data were collected in July and August 2025 using a structured online questionnaire. A total of 225 complete responses were collected from employees in 79 companies, representing 31.9% of the population of certified companies. Sampling procedures and country coverage are detailed in Umihanić and Sakić (2025), while Table 1 presents employee characteristics used for group comparisons and as control variables.

Respondents were grouped according to their companies' business activities. The majority (92.4%) were employed in the agri-food sector, including meat and poultry processing (34.2%), bakery products (15.1%), prepared foods and other food products (15.6%), dairy products (8.4%), oils and fats (5.3%), fruit and vegetable processing (4.4%), milling (2.7%), primary agriculture and aquaculture (5.8%), and beverages (0.9%). The remaining 7.6% of respondents were employed in trade, catering, hospitality, packaging production, and service activities.

Table 1. Sample characteristics (N = 225)

Characteristic	n	%	Characteristic	n	%
Country			**Job position**		
Bosnia and Herzegovina	168	74,7	Owner / management	27	12,0
Serbia	33	14,7	Quality, technology and control	87	38,7
Croatia	24	10,7	Production	51	22,7
Halal team member			Other functions	60	26,7
Yes	135	60,0	**Education**		
No	90	40,0	Secondary education or lower	50	22,2
Number of halal training sessions			University degree	116	51,6
None	44	19,6	Master's degree / doctorate	59	26,2
One	63	28,0	**Length of service in the company**		
Two	40	17,8	1–5 years	84	37,3
Three or more	78	34,7	6–10 years	54	24,0
Gender			11–20 years	61	27,1
Male	107	47,6	More than 20 years	26	11,6
Female	116	51,6			
Not disclosed	2	0,9			

Source: Authors' calculations

The study used the questionnaire described in Umihanić and Sakić (2025), comprising 17 halal competency items derived from BAS 1049:2023 and OIC/SMIIC 18:2021 (OIC/SMIIC, 2021), rated on a five-point importance scale (1 = not at all important; 5 = very important). Organisational efficiency was assessed through 15 statements on a five-point Likert scale (1 = strongly disagree; 5 = strongly agree), covering four dimensions: process management, internal halal audit, non-conformity management, and customer satisfaction.

Unlike the previous study, which analysed competencies as four composite dimensions, this study analyses competencies at the level of individual items, dimensions derived from factor analysis, and an overall halal competency index calculated as the mean of all 17 items (Cronbach's $\alpha = 0.970$). Two items concerning HrCCP analysis and hygiene requirements were assigned according to the conceptual logic of the KSAH framework, resulting in slightly different reliability coefficients for the knowledge and skills categories compared with those previously published. The overall organisational efficiency index was calculated as the mean of all 15 statements ($\alpha = 0.967$).

Data were analysed in several stages. The perceived importance of competencies was ranked using the mean, standard deviation, and proportion of "very important" ratings. The structure of halal competencies was examined using Principal Component Analysis (PCA) and varimax rotation, with the Kaiser–Meyer–Olkin measure and Bartlett's test of sphericity used to assess the suitability of the data (Hair et al., 2019). As the distributions of ratings deviated from normality and showed pronounced negative skewness, differences between groups were tested using the Mann–Whitney U test and the Kruskal–Wallis H test, with effect sizes reported.

The association between halal competencies and organisational efficiency was examined using hierarchical regression analysis. The first step included country, halal team membership, number of training sessions, job position, and tertiary education as control variables. The second step added either the overall halal competency index or the two PCA-derived dimensions (Tabachnick & Fidell, 2007), allowing assessment of their additional explanatory contribution after controlling for employee characteristics.

Results

The descriptive analysis of the perceived importance of individual competencies (Table 2) shows that all competencies received high ratings (mean values from 4.17 to 4.65), while the proportion of "very important" ratings ranged from 44.0% to 76.9%. The highest mean ratings were recorded for knowledge of hygiene and food safety requirements (4.65), knowledge of halal standards and the distinction between *halal*, *haram*, and *mashbooh* status (4.62), a sense of responsibility for the integrity of halal processes (4.58), knowledge of halal processes and procedures (4.57), and adherence to Islamic work ethics (4.57).

The lowest ratings were recorded for actively improving one's knowledge through participation in training (4.17), the ability to independently apply procedures and manage non-conformities (4.32), and effective communication and cooperation (4.34). Across the four categories, knowledge (4.57) and attitudes (4.56) were rated as more important than skills (4.41) and habits (4.36).

Table 2. Perceived importance of halal competencies

Competency	Mean	SD	% very important	Rank	α
Knowledge	**4,57**	**0,67**			**0,894**
Knowledge of Islamic teachings on halal	4,43	0,86	62,2	12	
Knowledge of halal standards (halal, haram, mashbooh)	4,62	0,72	72,9	2	
Knowledge of halal processes, procedures, and raw materials	4,57	0,77	71,1	4	
Knowledge of hygiene and food safety requirements	4,65	0,72	76,9	1	
Skills	**4,41**	**0,75**			**0,910**
Application of HrCCP analysis in production	4,47	0,86	66,2	8	
Management of halal documentation	4,47	0,81	63,1	8	
Planning and conducting internal audits	4,38	0,88	57,8	13	
Independent application of procedures and management of non-conformities	4,32	0,80	50,2	16	
Attitudes	**4,56**	**0,70**			**0,931**
Acting in accordance with religious values (amanah)	4,52	0,80	67,1	7	
Sense of responsibility for the integrity of halal processes	4,58	0,73	70,2	3	
Adherence to Islamic work ethics	4,57	0,79	72,4	4	
Awareness of the importance of personal contribution to halal integrity	4,56	0,75	68,0	6	

Competency	Mean	SD	% very important	Rank	α
Habits	**4,36**	**0,74**			**0,929**
Active improvement of knowledge (participation in training)	4,17	0,91	44,0	17	
Effective communication and cooperation	4,34	0,84	53,3	15	
Consulting responsible personnel in cases of uncertainty	4,46	0,83	62,7	10	
Active contribution to the implementation and improvement of procedures	4,38	0,85	57,3	13	
Adaptability and willingness to make additional efforts	4,45	0,77	59,1	11	
Overall halal competency index	**4,47**	**0,67**			**0,970**

Source: Authors' calculations

Principal component analysis (PCA) identified two substantively interpretable dimensions of halal competencies. The first, the technical-behavioural dimension (F1), comprises technical knowledge of processes and hygiene, all four skills, and all habits, totalling 11 items, with high internal consistency ($\alpha = 0.959$). The second, the value-normative dimension (F2), comprises knowledge of Islamic teachings, the distinction between *halal*, *haram*, and *mashbooh* status, and all four attitudes, totalling six items, also with high internal consistency ($\alpha = 0.945$).

Before rotation, the first component explained 68.5% of the total variance and the second an additional 6.8%. Together, the two components explained 75.3% of the variance (Table 3). The suitability of the data for PCA was confirmed by a high KMO value (0.952) and a statistically significant Bartlett's test ($\chi^2 = 4177.2$; $df = 136$; $p < 0.001$).

The composite measures formed on the basis of this classification were strongly correlated ($r = 0.825$), indicating that the two dimensions represent closely related components of a single halal competency construct, but with distinct substantive characteristics.

Table 3. Factor structure of halal competencies
(principal component analysis, varimax rotation)

Competency	F1 Technical-behavioural	F2 Value-normative
Halal documentation management	0,81	0,32
Independent application of procedures and management of non-conformities	0,81	0,32
Active contribution to the implementation and improvement of procedures	0,78	0,40
Application of HrCCP analysis in production	0,76	0,29
Effective communication and cooperation	0,76	0,43
Consulting responsible personnel in cases of uncertainty	0,76	0,42
Planning and conducting internal audits	0,75	0,41
Knowledge of halal processes, procedures, and raw materials	0,70	0,51
Knowledge of hygiene and food safety requirements	0,70	0,46
Active improvement of knowledge (participation in training)	0,65	0,38

Competency	F1 Technical-behavioural	F2 Value-normative
Adaptability and willingness to make additional efforts	0,63	0,58
Adherence to Islamic work ethics	0,28	0,87
Acting in accordance with religious values (amanah)	0,32	0,85
Knowledge of Islamic teachings on halal	0,26	0,82
Knowledge of halal standards (halal, haram, mashbooh)	0,48	0,76
Sense of responsibility for the integrity of halal processes	0,58	0,71
Awareness of the importance of personal contribution to halal integrity	0,55	0,70
Initial Eigenvalue / % of variance before rotation	11,65 / 68,5	1,15 / 6,8

Source: Authors' calculations. Factor loadings greater than 0.60 determine the assignment of items to factors.

The results of tests for differences between groups are presented in Table 4. Halal team members assigned greater importance to halal competencies than other employees, both for the overall index (4.57 versus 4.31; $p < 0.001$) and for both dimensions. The difference was more pronounced for the technical-behavioural dimension ($r = 0.31$) than for the value-normative dimension ($r = 0.23$). Employees who had attended at least one halal training session also rated competencies more highly than those who had not attended training (4.49 versus 4.38; $p = 0.045$), although the effect size was small ($r = 0.13$). The number of halal training sessions attended was not associated with statistically significant differences in competency ratings (Kruskal–Wallis $p = 0.249$). Based on these results, H1 was supported, with halal team membership showing a larger effect than participation in halal training.

Perceptions of the importance of halal competencies differed significantly by job position ($H = 19.39$; $p < 0.001$; $\eta^2 = 0.07$). The highest ratings were given by employees working in quality, technology, and control functions (4.62), followed by production employees (4.50), while owners and managers gave the lowest ratings (4.22). The difference was particularly pronounced for the technical-behavioural dimension, which employees in quality, technology, and control functions rated at a mean of 4.61, compared with 4.15 among owners and managers. Tertiary education was associated with higher ratings of the technical-behavioural dimension (4.48 versus 4.22; $p = 0.007$), while the difference for the value-normative dimension was not statistically significant ($p = 0.364$). As differences were identified according to both job position and level of education, H2 was supported. Respondents from Serbia and Croatia rated the technical-behavioural dimension more highly than respondents from Bosnia and Herzegovina ($p = 0.001$). Differences by length of service ($p = 0.617$) and gender ($p = 0.247$) were not statistically significant.

Table 4. Differences in the perceived importance of halal competencies according to employee characteristics

Characteristic	Overall index	p (r / η²)	Technical-behavioural	Value-normative
Halal team member: yes / no	4,57 / 4,31	<0,001 (0,31)	4,55 / 4,24 ***	4,62 / 4,44 ***
Halal training: yes / no	4,49 / 4,38	0,045 (0,13)	4,45 / 4,33 *	4,56 / 4,47 *
Tertiary education: yes / no	4,51 / 4,32	0,026 (0,15)	4,48 / 4,22 **	4,56 / 4,50
Job position		<0,001 (0,07)	***	**
Owner / management	4,22		4,15	4,35
Quality, technology, control	4,62		4,61	4,65
Production	4,50		4,44	4,61
Other functions	4,33		4,27	4,44
Country		0,004 (0,04)	**	
Bosnia and Herzegovina	4,42		4,35	4,53
Serbia	4,64		4,63	4,67
Croatia	4,59		4,66	4,46

Source: Authors' calculations. *Mean* values are presented. *P-values* are based on the Mann–Whitney U test (two groups) and the Kruskal–Wallis H test (multiple groups); effect sizes are reported as r for two groups and η^2 for multiple groups. * $p < 0.05$; ** $p < 0.01$; *** $p < 0.001$.

The associations of the overall halal competency index and the two identified dimensions with organisational efficiency were examined before conducting the regression analysis. The overall halal competency index was positively correlated with the overall organisational efficiency index ($r = 0.379$; $p < 0.001$). This correlation was slightly stronger than those previously reported for the individual KSAH dimensions (Umihanić & Sakić, 2025). The technical-behavioural dimension was consistently more strongly associated with all dimensions of organisational efficiency (r ranging from 0.347 for customer satisfaction to 0.400 for overall organisational efficiency) than the value-normative dimension (r ranging from 0.250 to 0.295).

Hierarchical regression analysis (Table 5) shows that the control variables explain between 8.6% and 15.7% of the variance in the individual dimensions of organisational efficiency. The number of halal training sessions and employment in quality-related functions were consistently associated with positive and statistically significant regression coefficients, while the coefficients for management positions were negative but not statistically significant. In the second step of the analysis, the overall halal competency index, reflecting employees' perceived importance of the competencies, was included in the regression models, increasing the explained variance by an additional 7.1 to 9.2 percentage points. All changes were statistically significant ($p < 0.001$). The standardised coefficient of the competency index ranged from 0.278 for process management to 0.317 for overall organisational efficiency, making it the strongest individual predictor in all models.

Unlike the previously published models based on the four KSAH dimensions of halal competencies, in which no predictors were statistically significant for process

management or non-conformity management, the present analysis found a statistically significant contribution of halal competencies to all four dimensions of organisational efficiency. When the two dimensions of halal competencies were introduced instead of the overall index, the technical-behavioural dimension remained a significant predictor of all outcomes (β ranging from 0.243 to 0.399), while the value-normative dimension made no independent statistically significant contribution (β ranging from −0.098 to 0.045; $p > 0.39$). Based on these results, H3 was supported, with the independent contribution of halal competencies to organisational efficiency being associated with the technical-behavioural dimension.

Table 5. Hierarchical regression of organisational efficiency dimensions on halal competencies

Predictor	Process management	Internal halal audit	Non-conformity management	Customer satisfaction	Overall efficiency
Step 1: Control variables (R^2)	0,157	0,144	0,131	0,086	0,151
Step 2: Model with competency index					
Number of halal training sessions (β)	0,161 *	0,202 **	0,193 **	0,150 *	0,192 **
Quality-related function (β)	0,161 *	0,171 *	0,150 *	0,141 *	0,172 *
Management (β)	–0,085	–0,094	–0,113	–0,107	–0,108
Halal team member (β)	0,075	0,026	0,024	–0,030	0,029
Halal competency index (β)	**0,278** ***	**0,288** ***	**0,299** ***	**0,292** ***	**0,317** ***
ΔR^2	0,071 ***	0,077 ***	0,082 ***	0,079 ***	0,092 ***
R^2 / Adjusted R^2	0,228 / 0,199	0,220 / 0,191	0,213 / 0,184	0,164 / 0,133	0,244 / 0,216
F	7,96 ***	7,63 ***	7,32 ***	5,31 ***	8,70 ***
Alternative Step 2: Two dimensions					
Technical-behavioural (β)	0,243 *	0,372 **	0,337 **	0,399 **	0,367 **
Value-normative (β)	0,045	–0,074	–0,028	–0,098	–0,039
Adjusted R^2	0,196	0,198	0,186	0,142	0,220

Source: Authors' calculations. Control variables also include country (Serbia and Croatia) and tertiary education, whose coefficients were not statistically significant in any model. β – standardised coefficient. * $p < 0.05$; ** $p < 0.01$; *** $p < 0.001$.

Discussion

The results confirm that employees in halal-certified agri-food companies consider halal competencies highly important, although the relative importance assigned to individual competencies varies. The highest ratings were given to competencies relating to the fundamental distinction between what is permitted and prohibited (*halal and haram*), hygiene requirements, and a personal sense of responsibility. These competencies are closely linked to the essence of halal integrity and are readily recognised in everyday work. The lowest ratings were given to competencies requiring proactivity and continuous effort, particularly participation in training, independent management of

non-conformities and communication. This pattern indicates that employees attach greater importance to competencies directly related to compliance with halal rules and values than to those involving continuous development, independence, and cooperation. These results are consistent with the observations of Voak and Fairman (2020), who highlighted the challenges of human resource development in halal supply chains and the need for competency-based training.

The two-dimensional structure of halal competencies conceptually corresponds to the distinction between hidden and visible components of competency discussed by Spencer and Spencer (1993). A similar distinction was proposed by Voak, Fairman, and Wahyuni (2023), who differentiated socio-cultural and ethical competencies from technical and operational competencies, although their model was not empirically tested. Unlike the original four-dimensional KSAH structure, knowledge competencies were distributed between the two dimensions according to their value-related or operational content. This suggests that employee development should integrate an understanding of halal values with their practical application. A similar perspective is presented by Harahap et al. (2024), who link human resource development in the halal industry to technical skills, knowledge, attitudes, and work ethics.

The difference in the predictive value of the two dimensions has important implications for halal system management. Although employees assigned greater importance to value-normative competencies, only the technical-behavioural dimension made an independent statistically significant contribution to organisational efficiency when both dimensions were included in the regression models. This is consistent with Umihanić and Sakić (2025), who identified skills and habits, but not knowledge and attitudes, as independent predictors of selected efficiency dimensions. The findings also correspond with Rehmani et al. (2020) on the relationship between high-performance work systems and organisational effectiveness, and Rafiki and Abdul Wahab (2016) on the importance of training and education for halal certification. They suggest that commitment to halal values needs to be supported by operational knowledge, skills, and consistent work habits to contribute to organisational efficiency.

The greater importance assigned to competencies by halal team members suggests that direct involvement in halal system activities may be more influential than participation in training alone. Particularly concerning is the lower importance assigned by owners and managers, given their responsibility for employee development and halal team organisation. Voak, Fairman, and Helmy (2024) also emphasise the need for systematic development of leadership competencies in halal supply chains. Greater management involvement may therefore support the long-term effectiveness of halal systems.

The results should be interpreted in light of several limitations. The cross-sectional design does not allow causal conclusions, and it is also possible that well-developed halal systems shape employees' awareness of competencies rather than the reverse. The study measured perceived importance rather than actual competency levels, indicating a need to confirm the findings through objective assessments. All variables were

collected using the same instrument at the same point in time, creating the possibility of common method bias. In addition, pronounced negative skewness may limit variability and affect the estimated strength of associations. The sample was not proportionally distributed across countries, so differences between countries should be interpreted with caution.

Conclusions

This study extends the previously developed halal competency framework based on the four-dimensional KSAH approach by analysing individual competencies, their structure, and their association with organisational efficiency. The results show that employees assign high importance to halal competencies. The analysis of the 17 individual competencies identified two interrelated dimensions: value-normative and technical-behavioural. Competencies related to halal integrity, hygiene requirements, and personal responsibility received the highest ratings, while continuous training, independent management of non-conformities, and communication received lower ratings.

The perceived importance of competencies was higher among halal team members and employees working in quality-related functions, while owners and managers assigned the least importance to these competencies. The overall halal competency index made an additional contribution to explaining organisational efficiency, while the technical-behavioural dimension made an independent statistically significant contribution when both dimensions were included in the model simultaneously.

The results suggest that employee development should place greater emphasis on operational knowledge, skills, and work habits, alongside an understanding of the values underlying halal. The analysis also highlights the need for greater involvement of management and employees in halal system activities. Future research should confirm the two-factor structure using an independent sample and examine actual, rather than merely perceived, competencies and their contribution to measurable outcomes of halal system efficiency.

Conflict of Interest

The authors declare that there is no conflict of interest. The second author was previously employed by the Agency for Halal Quality Certification, which certifies some of the companies included in the sample. Data were collected anonymously and were not used for certification purposes.

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INFLATION AND STOCK RETURNS OF ENERGY COMPANIES: IMPLICATIONS FOR THE COSTS AND COMPETITIVENESS OF THE AGRO-INDUSTRY OVER THE PERIOD 2015–2023, WITH A FOCUS ON AI

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A B S T R A C T

This study examines how inflation affects stock prices. Given the limitations of the Efficient Market Hypothesis and the emergence of contemporary approaches emphasizing nonlinearity in financial data, the study investigates the nature of the relationship between inflation and stock returns. The empirical analysis employs OLS and quantile regression. The final parameter estimates indicate that the data deviate from a normal distribution, thereby providing a statistical rationale for the application of quantile regression. In other words, the results suggest that the relationship between inflation and stock prices is not uniform but varies depending on prevailing market conditions. These findings underscore the importance of applying advanced econometric techniques and AI methods in financial market analysis.

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Introduction

An efficient capital market is one in which stock prices fully reflect all relevant available information. Market efficiency may arise when investors behave rationally and access to information does not involve transaction costs. The available evidence suggests that information is widely accessible. Under such circumstances, the concept of the Efficient Market Hypothesis (EMH) provides an essential theoretical framework for understanding the functioning of global capital markets. This hypothesis is based on the assumption that all available information is already incorporated into asset prices (Butet & Kesuma, 2025).

Grossman and Stiglitz (1980) argue that perfectly informationally efficient markets cannot exist, as such efficiency would eliminate the incentives for investors to acquire information. Market efficiency varies depending on the prevailing economic environment, including periods of economic growth, crisis, and stability, implying that the effects of macroeconomic factors, such as inflation, are not constant. Accordingly, the impact of inflation and other macroeconomic variables may differ depending on market conditions, highlighting the need for advanced methodological approaches capable of capturing heterogeneity and nonlinear relationships. In this context, quantile regression represents a suitable analytical tool, as it enables the examination of effects across different points of the conditional distribution of the dependent variable (Jiang & Li, 2020). Since investors are primarily concerned with asset returns expressed in real terms, uncertainty surrounding inflation represents a potentially significant source of risk. In this context, Moerman and van Dijk (2010) emphasize the importance of inflation risk in asset pricing, noting that previous studies have examined the extent to which different asset classes provide protection against inflation. The implications of inflation for financial market development were also investigated by Barnes et al. (1999), who suggest that persistent inflation may adversely affect financial markets, including equity markets, with negative effects potentially being pronounced even in economies experiencing low to moderate inflation rates. One mechanism underlying this relationship involves a reduction in real asset returns, which may exacerbate credit market frictions, restrict the availability of funds for investment financing, and negatively affect long-term real economic activity.

Beyond its effects on real returns and financial market development, an important issue concerns how investors form expectations and adjust their investment decisions in response to inflationary developments. Schnorpfeil et al. (2025) find that investors' expectations regarding the impact of inflation on stock returns are heterogeneous and, on average, excessively optimistic. Their findings indicate that information about negative stock returns during previous inflationary periods reduces investors' expected returns. These changes in expectations also influence actual investment behavior, contributing to a decline in stock purchases. Similarly, Thorbecke (2025) examines the influence of inflation expectations on financial asset prices, suggesting that investors tend to sell assets adversely affected by inflation and purchase assets that benefit from

rising inflation. However, the empirical findings indicate that investors may respond to inflationary pressures with a delay, adjusting their investment decisions only after actual inflation begins to accelerate.

The relationship between inflation expectations and equity market performance was further investigated by Chiang (2024), who examined 15 international stock markets and identified a negative association between expected inflation and real stock returns. The findings suggest that news about rising inflation increases equity market volatility, which subsequently has an adverse effect on stock returns. Furthermore, changes in monetary policy, particularly interest rate increases implemented by the Federal Reserve, were found to have nonlinear effects on real stock returns. The importance of inflation and interest rates during periods of economic disruption was also examined by Li et al. (2026), who analyzed stock returns in advanced economies across different crisis periods. Their findings indicate that inflationary shocks following the COVID-19 pandemic contributed to increased stock return volatility in the United States, the European Union, and the United Kingdom, whereas the effects on the Japanese market were less pronounced. These results highlight differences in the sensitivity of national equity markets to inflationary developments.

Nevertheless, empirical research has not reached a consensus regarding the direction and magnitude of the relationship between inflation and stock returns. Chirilă and Chirilă (2026) emphasize that some studies support the Fisher hypothesis, whereas others identify a negative relationship between inflation and stock returns, particularly in the short run. The authors highlight the importance of the investment horizon in explaining this relationship. Against this background, they investigate the effects of headline, expected, and unexpected inflation on sectoral stock returns in Poland using GARCH models and quantile regression techniques. The relevance of investment horizons and the measurement of inflation expectations is also emphasized by Taşkıran (2026), who examines the responses of the Turkish stock market to inflation surprises over the period 2018–2025. The findings suggest that the relationship between inflation surprises and stock returns depends on how inflation expectations are measured and the time horizon considered, while some market responses are statistically insignificant.

Differences in empirical findings also highlight the importance of examining nonlinearities and asymmetries in equity market responses to inflationary shocks. In this context, Ayadi, Ben Jedidia, and Ben Mbarek (2026) investigate equity market responses in G7 economies, considering the possibility that the effects of unexpected inflation on real stock returns depend on both the prevailing inflation environment and the direction of inflation shocks. During periods of elevated inflation, positive inflation surprises may trigger more pronounced declines in stock prices due to expectations of tighter monetary policy, whereas similar shocks may produce weaker effects under low and stable inflation conditions. Furthermore, the negative impact of inflation exceeding expectations may be stronger than the positive impact associated with inflation falling below expectations.

In addition to the prevailing inflation environment and the direction of inflation shocks, the composition of inflation is another important factor in understanding equity market movements. Fang et al. (2026) investigate the relationship between inflation risks and returns across different financial asset classes, paying particular attention to differences among inflation components. Their findings indicate that stock returns respond negatively to core inflation shocks, whereas their relationship with energy inflation is positive. The authors further suggest that the negative response to core inflation cannot be fully explained by anticipated changes in monetary policy, emphasizing the importance of distinguishing between different sources of inflationary pressures. Another important dimension of the inflation–equity relationship concerns the role of inflation risk in financial asset valuation. Letourneau, Power, and Smith (2026) suggest that an increase in expected inflation risk is associated with lower current stock prices and higher expected stock returns. Moreover, firms' sensitivity to inflationary developments may depend on their ability to pass rising production costs on to consumers through higher selling prices. Taken together, the reviewed studies suggest that the relationship between inflation and stock returns is neither uniform nor necessarily linear.

In addition to these considerations, the relationship between technological transformation and corporate performance represents another important dimension of contemporary economic research. In this regard, Milanović et al. (2026) examine the relationship between digitalization and the financial performance of companies operating in the agricultural sector, highlighting the strategic importance of technological transformation while also recognizing that the associated organizational and implementation costs may negatively affect company returns. Their findings provide an additional perspective on the relationship between technological development and corporate performance, particularly in sectors that are highly relevant to the broader agro-industrial environment. This perspective is important for understanding how digital transformation, alongside macroeconomic pressures such as inflation and rising energy costs, may influence business performance and competitiveness across interconnected economic sectors. Instead, it depends on inflation expectations, the characteristics of inflationary shocks, investment horizons, monetary conditions, and the specific features of individual financial markets. The diversity of empirical findings highlights the importance of considering both the direct effects of inflation on equity returns and the mechanisms through which inflationary developments influence investor expectations, market volatility, and financial asset valuations. Following the theoretical framework of market efficiency, a substantial body of research has examined the relationship between inflation and stock prices. Early studies suggest the existence of a negative relationship between inflation and stock returns. In particular, Fama (1981) demonstrates that inflation has a negative effect on real stock returns, a finding commonly explained by the impact of inflation on real economic activity.

On the other hand, according to the Fisher effect (Fisher, 1930), nominal returns should incorporate expected inflation, implying that stocks may serve as a hedge against inflationary pressures. Consistent with this view, some studies have identified a positive long-run relationship between inflation and stock prices (Boudoukh & Richardson, 1993).

However, subsequent research suggests that the relationship between inflation and capital markets is not unambiguous. Boyd et al. (2005) demonstrate that the effects of inflation depend on prevailing economic conditions, while Geske and Roll (1983) point to the possibility of reverse causality between inflation and stock prices. These findings suggest the existence of complex and nonlinear relationships that may not be adequately captured by conventional linear models.

The subject of this study is the analysis of the impact of inflation on the stock prices of companies operating in the energy sector, with particular emphasis on Chevron Corporation, ExxonMobil Corporation, and ConocoPhillips. The research focuses on examining the dynamics and nature of the relationship between macroeconomic factors and capital markets, recognizing that this relationship is not uniform and may vary depending on prevailing market conditions.

The primary objective of this study is to determine the nature and magnitude of the effect of inflation on the stock prices of the selected companies and to examine whether this effect varies across different quantiles of the distribution.

Research Results

The analysis uses daily stock market data obtained from Stooq, with company stock returns serving as the dependent variable and inflation as the independent variable. Based on the study conducted by Kádárová et al. (2023), the following equation is proposed:

$Y_{it} = \alpha + \beta X_{it} + \varepsilon_{it}$ where:

Y_{it} – denotes the dependent variable for company *i* at time *t*;

X_{it} – denotes the independent variable for company *i* at time *t*;

α – represents the intercept;

ε_{it} – denotes the error term for company *i* at time *t*.

Table 1. Descriptive Statistics

	Inflation	Chevron Corporation	Exxonmobil Corporation	ConocoPhillips
Mean	3.761	5.315	5.357	5.457
Standard deviation	26.153	0.958	0.886	0.769
Median	1.762	5.810	5.630	5.682
Minimum	-0.136	1.838	1.825	1.514
Maximum	8.001	5.999	5.999	5.999
Skewness	2.153	-2.364	-2.536	-3.710
Kurtosis	1.800	8.472	10.117	17.056

Source: Authors' calculations

The descriptive statistics reveal specific characteristics of the distributions of inflation and the stock prices of the selected companies, which are relevant to the subsequent econometric analysis. Regarding inflation, both the mean (3.761) and the median (1.762) are positive, suggesting that inflationary conditions predominated during the period under observation. However, the fact that the mean exceeds the median, together with a skewness coefficient of 2.153, indicates pronounced positive skewness, reflecting the potential presence of occasional inflationary spikes. The standard deviation is exceptionally high (26.153), suggesting substantial variability in inflation over time. The kurtosis value of 1.800 is below the benchmark value of 3, indicating a distribution with relatively light tails compared with the normal distribution.

On the other hand, the estimated parameters for the companies analyzed in this study exhibit similar statistical characteristics. The mean values fall within a very narrow range, while the standard deviations are relatively low. Nevertheless, the skewness coefficients indicate pronounced asymmetry in the distributions. These findings are consistent with developments in financial markets, given that stock returns are highly sensitive to emerging shocks.

Table 1 presents the results obtained using Ordinary Least Squares (OLS) regression. These results indicate that the relationship between the variables is statistically significant, although differences can be observed in the direction and magnitude of the estimated effects.

Table 2. Linear Regression – Ordinary Least Squares (OLS)

Company	OLS coefficient
Chevron Corporation	2.2848**
ConocoPhillips	-2.5575**
Exxonmobil Corporation	-0.0476***

Source: Authors' calculations. *, **, and *** denote statistical significance at the 1%, 5%, 10% levels, respectively.

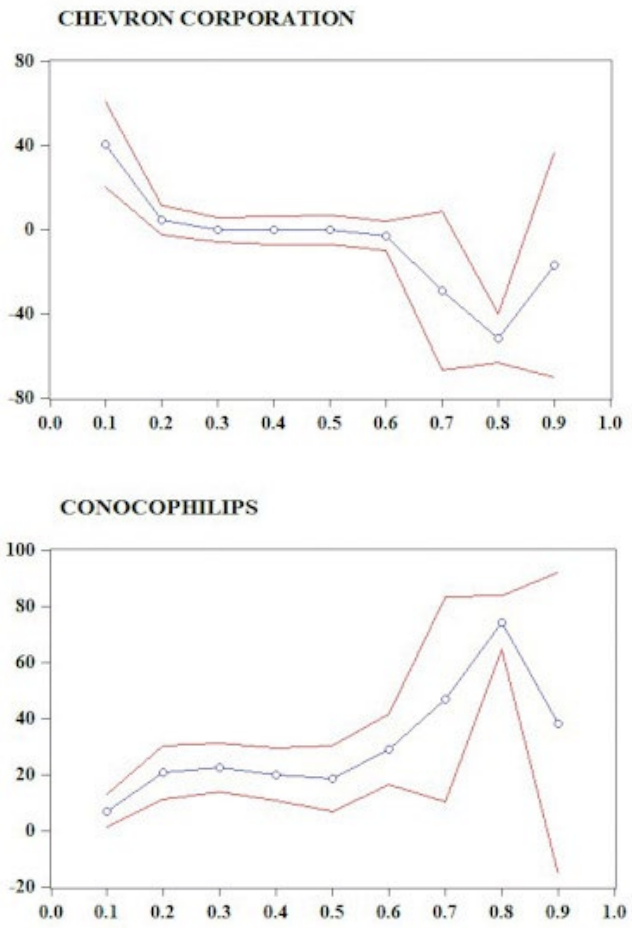
The first company examined is Chevron Corporation, for which the estimated coefficient is 2.2848. This coefficient is statistically significant and indicates a positive relationship between inflation and the company's stock price. The result suggests that an increase in inflation is associated with an increase in Chevron's stock price. One possible explanation is that energy companies may benefit from inflationary pressures, particularly during periods of rising oil and energy prices, which can contribute to higher revenues and improved market valuations.

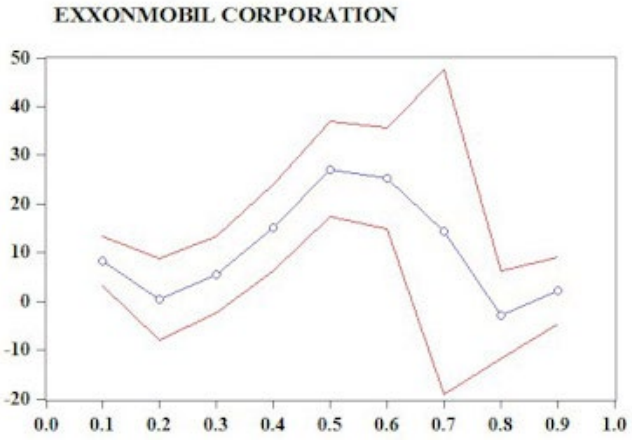
The next company examined exhibits a different pattern. In the case of ConocoPhillips, the estimated coefficient is negative and statistically significant (-2.5575), indicating a negative relationship between inflation and the company's stock price. This finding suggests that higher inflation is associated with a decline in the value of ConocoPhillips shares. The result may indicate greater sensitivity to macroeconomic instability or the influence of company-specific business factors that contribute to declining stock prices under conditions of elevated inflation.

The final company examined, ExxonMobil Corporation, exhibits a negative coefficient (-0.0476). Given the comparatively weaker level of statistical significance, this result may indicate a weak negative relationship between inflation and the company's stock price. It may also suggest that ExxonMobil is relatively more resilient to inflationary shocks than the other companies included in the analysis.

Overall, the coefficients obtained using Ordinary Least Squares (OLS) regression indicate that inflation does not have a uniform effect across all companies in the energy sector. While a positive relationship is observed for some companies, a negative relationship is identified for others, suggesting heterogeneity in the effects of inflation. These findings further justify the application of quantile regression, which enables a more in-depth examination of how the effects of inflation vary across different points of the conditional distribution of the dependent variable.

Figure 1. Graphical Representation of the Effects of Inflation on Company Stock Returns Across Quantiles





Source: Author's own illustration

The graphs presented above provide a consistent representation of the changes in inflation coefficients across different quantiles of the stock price distribution, enabling a more in-depth analysis compared with conventional OLS regression. This approach is particularly relevant in the context of applying advanced methods such as artificial intelligence, as it facilitates the identification of nonlinear and heterogeneous effects.

First, Chevron exhibits a significant variation in the effect of inflation across the quantile distribution. In the lower quantiles (0.1–0.3), the impact of inflation is positive and relatively strong, indicating that inflation has a stimulating effect under conditions of lower stock prices. At the median quantiles, this effect becomes relatively stable and approaches zero, suggesting a reduced sensitivity to inflation.

The higher quantiles indicate a sharp decline in the coefficient into negative territory, suggesting that inflation has a negative impact when stock prices are high. This pattern may be attributable to heightened market expectations or price corrections under inflationary pressures. The wide confidence intervals at higher quantiles indicate greater uncertainty and the presence of extreme values.

For the next company, ConocoPhillips, a predominantly positive effect of inflation is observed across most of the quantile distribution. The effect is moderate in the lower and middle quantiles, whereas a substantial increase in the coefficient occurs in the higher quantiles (0.7–0.8). These findings suggest that inflation has a strong positive impact under conditions of high stock prices.

This finding may suggest that the company has the capacity to pass inflationary pressures on to the prices of its products, thereby increasing its revenues. However, a decline in the coefficient, accompanied by substantial variability, is observed at the highest quantile (0.9), suggesting a less stable relationship under extreme market conditions.

The next company, ExxonMobil, exhibits a nonlinear relationship between inflation and stock prices. In the lower quantiles, the effect is weak and variable, whereas it reaches its peak in the middle quantiles (0.4–0.6), indicating that inflation exerts its strongest positive influence within this part of the distribution.

However, an examination of the higher quantiles reveals a sharp decline in the coefficient, with a transition into negative territory. This suggests that inflation may have a destabilizing effect when stock prices are high. These findings confirm the presence of asymmetric effects that cannot be captured by conventional OLS models.

The parameters estimated through quantile regression have direct implications for the application of artificial intelligence methods in finance. First, the observed nonlinearity and heterogeneity of inflation effects indicate that traditional linear models, such as OLS, may be insufficient to adequately model the relationship between macroeconomic variables and stock prices. For this reason, contemporary AI models, such as neural networks, random forests, and gradient boosting, offer advantages because they can capture complex, nonlinear dependencies in the data. These findings are also supported by the studies of Campisi et al. (2024) and Ravichandran and Afjal (2025).

Furthermore, quantile regression can serve as a bridge between classical econometrics and AI-based approaches, as it enables the analysis of different parts of the distribution and the identification of asymmetric effects. These results are particularly useful as inputs for AI models, as they indicate that the impact of inflation is not constant but rather depends on the level of stock prices.

Conclusion

The findings obtained in this study indicate, first and foremost, that inflation, as a macroeconomic variable, does not affect stock prices uniformly across all companies. Its impact is markedly nonlinear and depends on the position within the distribution of the variable under consideration. While OLS regression estimates the average effect of inflation, quantile regression reveals substantial heterogeneity, demonstrating that both the direction and magnitude of this effect vary across different quantiles. Notable differences emerge across companies, with some exhibiting a positive relationship with inflation and others a negative one, highlighting the specific characteristics of their business models and their varying degrees of sensitivity to macroeconomic factors.

Descriptive statistics further confirm the presence of asymmetry, high variability, and extreme values, suggesting that the data may deviate from a normal distribution. These characteristics provide a methodological rationale for employing quantile regression as a more suitable analytical approach than conventional linear models. Furthermore, the observed nonlinearity and complexity of the relationship between inflation and stock prices underscore the relevance of contemporary artificial intelligence and machine learning methods. These approaches enable the modelling of complex dependencies and may contribute to more accurate predictions of financial market movements. Ultimately, the findings contribute to a deeper understanding of the dynamics between

macroeconomic factors and capital markets, highlighting the need to incorporate advanced econometric techniques and AI-based methods into future research.

Conflict of interests

The authors declare no conflict of interest.

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DEVELOPING THEMATIC ROUTES FOR SUSTAINABLE TOURISM DEVELOPMENT IN THE ŠUMADIJA AND POMORAVLJE REGION: LEGAL AND PROJECT MANAGEMENT PERSPECTIVES

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ABSTRACT

This paper examines perceptions of the importance of thematic routes for the sustainable development of tourism in the Šumadija and Pomoravlje region, with particular emphasis on the legal and managerial frameworks that support their development. The integration of natural and cultural heritage, gastronomy, local traditions, and tourism infrastructure can enhance regional attractiveness and competitiveness. An empirical study was conducted on a sample of 260 respondents using a structured questionnaire with profile questions and six dimensions measured on a five-point Likert scale. Data were analyzed using descriptive statistics, the chi-square test, the Mann-Whitney U test, and the Kruskal-Wallis test. The findings indicate strong support for thematic routes as a means of promoting local economic development, preserving cultural and natural heritage, and encouraging community participation. No statistically significant differences were identified according to gender, respondent status, or educational level. The results confirm the potential of thematic routes as an instrument for sustainable tourism and regional development.

Introduction

The development of thematic routes has emerged as an innovative approach to enhancing tourism offerings, gaining increasing importance within the broader framework of sustainable tourism and regional development. By integrating natural,

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cultural, historical, gastronomic, and social resources into a cohesive tourism product, thematic routes enable visitors to experience destinations through carefully curated thematic narratives (Dejanović et al., 2024). Such an approach supports destination differentiation, strengthens market positioning, encourages more balanced territorial development, and contributes to the preservation of local identity (Terzić et al., 2014). The multidimensional character of thematic routes makes them a valuable instrument for sustainable tourism development. They facilitate the integration of diverse tourism products, including cultural and historical heritage, gastronomy, wine tourism, natural attractions, and religious sites, thereby creating opportunities for economic growth while simultaneously supporting environmental conservation and heritage protection (Mitrović et al., 2023).

Previous studies have identified several factors that influence the success of thematic routes, including clearly defined themes, strong cooperation between public and private stakeholders, adequate infrastructure, digitalization, and continuous performance monitoring (El Archi et al., 2023; Pedrosa et al., 2022; Rodrigues et al., 2023). From a project management perspective, the development of thematic routes involves defining objectives, identifying and evaluating resources, allocating responsibilities, planning financial and human resources, selecting partners, and establishing performance indicators (PMI, 2021). This process typically includes inventorying tourism assets, assessing their attractiveness and accessibility, consulting local stakeholders, and selecting locations based on economic, social, cultural, and environmental criteria (Cai et al., 2020; Latinović et al., 2023; Lin et al., 2024; Meyer, 2004; Pentz, 2024). Collaboration among local authorities, tourism organizations, businesses, agricultural producers, and heritage management institutions is essential for ensuring the successful implementation and long-term sustainability of rural tourism and thematic routes (Ilić et al., 2024; Dejanović & Lukić Nikolić, 2024).

The successful development of thematic routes also depends on an appropriate legal and institutional framework. In Serbia, tourism development is supported by legislation regulating tourism, hospitality services, nature protection, and cultural heritage management, providing the basis for sustainable resource use and the preservation of natural and cultural assets. Compliance with these regulations is particularly important when thematic routes include protected areas and heritage sites, ensuring that tourism development remains aligned with conservation objectives and long-term sustainability principles (Santos-Roldán et al., 2020; Trišić et al., 2020).

This paper examines the potential for developing thematic routes in the Šumadija and Pomoravlje region, an area characterized by rich natural and cultural resources and significant opportunities for sustainable tourism development. The paper focuses on identifying key tourism assets, exploring opportunities for connecting attractions into integrated route networks, and assessing their suitability for contemporary tourist demands. Particular attention is given to the potential impacts of thematic routes on local communities, including economic and social benefits, as well as the preservation of natural and cultural heritage.

Theoretical framework and hypotheses development

Thematic routes represent an increasingly important instrument for the diversification and sustainable development of tourism destinations. By linking natural, cultural, gastronomic, and social resources into an integrated tourism product, they create opportunities for destination branding, extension of tourist stays, spatial distribution of visitor flows, and preservation of local identity (Buckley, 2012; Meyer, 2004; Terzić et al., 2014). Their ability to simultaneously generate economic benefits, support heritage conservation, and improve the quality of life of local communities positions thematic routes as an important mechanism for achieving sustainable tourism objectives (Mitrović et al., 2023). Sustainable tourism emphasizes the balanced integration of economic, social, and environmental dimensions of development through the responsible use of resources and active stakeholder participation in decision-making processes (UN Tourism, n.d.).

The Šumadija and Pomoravlje region possesses substantial resources that provide a strong foundation for thematic route development. Its natural attractions include mountain landscapes, river valleys, caves, springs, and waterfalls, notably the Resava Cave, Krupaj Spring, and Veliki Buk Waterfall. Integrating these attractions into thematic routes can create tourism experiences that combine education, recreation, culture, and nature while respecting conservation requirements and maintaining site authenticity (Richards, 2018; Timothy & Boyd, 2003). An additional development opportunity lies in linking tourism with agriculture, gastronomy, and local traditions. Wineries, distilleries, rural households, traditional food products, and local festivals can be integrated into gastronomic, wine, and rural tourism routes, contributing to local product promotion, regional value chains, and rural income generation (Hall et al., 2003; Long, 2004; Sims, 2009).

Combining cultural heritage sites, natural attractions, wineries, and agricultural households into interconnected tourism experiences can increase visitor expenditures, extend length of stay, and distribute tourism benefits across a wider geographical area (Hall, 2015; Novelli, 2005; Rodrigues et al., 2023). However, thematic route development is often constrained by infrastructure disparities, limited financial resources, insufficient stakeholder coordination, seasonality, and the risk of excessive commercialization of cultural heritage (Božić & Tomić, 2016; Pedrosa et al., 2022; Zouridaki et al., 2024). Addressing these challenges requires an integrated approach that combines legal, organizational, economic, and infrastructural measures while ensuring community participation and continuous monitoring of tourism impacts.

Building on these theoretical and developmental considerations, this paper examines how local residents, tourists, entrepreneurs, and institutional representatives perceive the role of thematic routes in enhancing tourism development, supporting local economies, and preserving cultural and natural heritage. Understanding these perceptions provides valuable insights into the opportunities and limitations associated with thematic route development in Šumadija and Pomoravlje and contributes to future tourism planning and management strategies.

Based on the theoretical background, the following hypotheses are proposed:

H1: Respondents positively evaluate the importance of thematic routes in Šumadija and Pomoravlje, particularly regarding their contribution to local economic development, preservation of cultural and natural heritage, promotion of local gastronomy, and integration of tourism infrastructure.

Sub-hypotheses are:

H1.1: There are statistically significant differences between male and female respondents in their perceptions of the importance of thematic routes and their contribution to tourism development.

H1.2: Statistically significant differences exist among local residents, tourists, entrepreneurs, and institutional representatives regarding their perceptions of the importance of thematic routes and their contribution to local development.

H1.3: Respondents with different educational backgrounds differ significantly in their perceptions of the importance of thematic routes, heritage preservation, and their contribution to tourism development.

Materials and methods

To achieve the research objectives, an empirical study was conducted using a structured questionnaire administered to 260 respondents, including local residents, tourists, entrepreneurs, and institutional representatives. Data were collected through an online survey (Google Forms) over a three-week period.

The questionnaire consisted of socio-demographic questions and 24 statements rated on a five-point Likert scale (1 = strongly disagree; 5 = strongly agree). The statements were grouped into six dimensions: (1) importance of thematic routes, (2) natural resources and attractions, (3) cultural and historical heritage, (4) gastronomy and local traditions, (5) tourism integration and infrastructure, and (6) sustainability and the role of the local community.

The sample included 124 men (47.7%) and 136 women (52.3%). Regarding education, 11.5% had primary education, 32.3% secondary education, and 56.2% higher education qualifications. Respondents comprised 120 local residents (46.2%), 70 tourists (26.9%), 36 entrepreneurs (13.8%), and 34 institutional representatives (13.1%).

Data were analyzed using IBM SPSS Statistics 23. Chi-square tests were used to examine response distributions, while Mann-Whitney U and Kruskal-Wallis tests were applied to assess differences according to gender, educational level, and stakeholder status ($p < 0.05$).

Research results

The results indicate a generally positive perception of thematic routes in Šumadija and Pomoravlje. Most respondents recognized their contribution to local economic development (76.9%), the promotion of natural and cultural heritage (76.2%), and

the reduction of tourism seasonality (71.5%), confirming their potential to enhance destination attractiveness and support sustainable tourism development.

Natural resources and cultural heritage were identified as key foundations of thematic route development. Positive attitudes were expressed toward the role of natural resources (74.6%), environmental preservation (73.1%), accessibility to attractions (69.2%), and the integration and preservation of cultural and historical heritage (75.4%-81.5%). These findings suggest that respondents perceive natural and cultural assets as essential elements of destination competitiveness and regional identity. Their inclusion in thematic routes should therefore be accompanied by appropriate accessibility, conservation measures, and sustainable management practices.

Gastronomy and local traditions also received strong support. Respondents positively evaluated the inclusion of local products and traditional food (83.1%), gastronomy-based experiences (80.8%), and traditional crafts and customs (75.4%). However, perceptions of their direct economic contribution were more moderate (55.4%), indicating stronger recognition of their cultural and tourism value than of their measurable economic effects.

The findings further emphasize the importance of **tourism integration and infrastructure**. Respondents supported the integration of tourism content (75.4%), while transport infrastructure and road signage received the highest level of agreement (84.6%). Accommodation and hospitality services were also recognized as important contributors to visitor satisfaction (70.8%). In contrast, opinions regarding digital guides and information systems were more divided, suggesting that respondents continue to prioritize physical infrastructure and service quality.

Sustainability emerged as another critical dimension. Most respondents agreed that local communities should benefit from thematic route development (75.4%), that natural and cultural resources should be preserved (76.9%), and that tourism impacts should be continuously monitored (75.4%). At the same time, only 37.3% believed that sustainability principles are adequately implemented in practice, indicating a gap between the recognized importance of sustainability and its perceived application.

Overall, the results suggest that successful thematic route development requires an integrated approach combining natural and cultural resources, gastronomy, infrastructure, stakeholder cooperation, and sustainability principles. Such an approach can strengthen destination competitiveness while contributing to sustainable regional development.

Statistical tests results

Table 1 presents the Chi-square test results examining response distributions across the six questionnaire dimensions.

Table 1. Results of the analysis of the Chi-square test

Dimension	**5**	**4**	**3**	**2**	**1**	Sum	χ^2 (Chi-square)	p-value
Perception of the importance of theme routes	320	268	152	152	148	1040	62.538	< 0.001
Importance of natural resources and attractions	444	310	144	86	56	1040	260.058	< 0.001
Cultural - historical heritage	476	214	128	62	34	1040	353.942	< 0.001
Gastronomy and local tradition	434	382	134	54	36	1040	336.846	< 0.001
Interaction - infrastructure	390	336	166	78	70	1040	209.654	< 0.001
Sustainability and the role of the community	420	372	156	52	40	1040	305.538	< 0.001

Source: Authors

The χ^2 analysis revealed significant deviations from a uniform distribution across all dimensions ($p < 0.001$), with responses concentrated in the agreement categories. The strongest consensus was observed for cultural heritage ($\chi^2 = 353.94$), gastronomy ($\chi^2 = 336.85$), sustainability ($\chi^2 = 305.54$), and natural resources ($\chi^2 = 260.06$), whereas opinions were more diverse regarding the general importance of thematic routes ($\chi^2 = 62.54$).

The Mann–Whitney U test was applied to assess gender differences in perceptions of thematic route development. Although women recorded higher mean scores across all examined dimensions, the statistical significance of these differences was determined by the corresponding *p*-values presented in Table 2.

Table 2. The Man-Whitney U test – Gender results

Dimension	**Mean ± SD (men / women)**	**p-value**
Perception of the importance of theme routes	M: 4.2 ± 0.6 / Ž: 4.5 ± 0.5 (n=124/136)	0.082
Importance of natural resources and attractions	M: 4.1 ± 0.7 / Ž: 4.3 ± 0.6 (n=124/136)	0.115
Cultural - historical heritage	M: 4.0 ± 0.8 / Ž: 4.4 ± 0.5 (n=124/136)	0.071
Gastronomy and local tradition	M: 4.3 ± 0.6 / Ž: 4.5 ± 0.5 (n=124/136)	0.084
Interaction - infrastructure	M: 4.1 ± 0.7 / Ž: 4.3 ± 0.6 (n=124/136)	0.143
Sustainability and the role of the community	M: 4.2 ± 0.6 /Ž: 4.4 ± 0.5 (n=124/136)	0.067

Source: Authors

As shown in Table 2, women consistently reported higher mean scores than men across all dimensions. However, since all *p*-values exceeded 0.05, no statistically significant gender differences were identified. Consequently, H1.1 was not supported.

The Kruskal–Wallis test was applied to examine whether perceptions of thematic routes and their contribution to tourism development differed among local residents, tourists, entrepreneurs, and institutional representatives. The results are summarized in Table 3.

Table 3. The Kruskal-Wallis test – differences results

Dimension	Resident (n)	Tourist (n)	Entrepreneur (n)	Institution representative (n)	p-value
Perception of the importance of theme routes	4.12±0.65	4.05±0.72	4.10±0.68	4.08±0.70	0.87
Importance of natural resources and attractions	4.15±0.60	4.08±0.66	4.12±0.63	4.10±0.61	0.92
Cultural - historical heritage	4.10±0.62	4.06±0.69	4.08±0.65	4.09±0.66	0.95
Gastronomy and local tradition	4.08±0.67	4.04±0.70	4.07±0.68	4.05±0.69	0.89
Interaction - infrastructure	4.06±0.64	4.03±0.66	4.05±0.65	4.04±0.67	0.91
Sustainability and the role of the community	4.12±0.63	4.08±0.67	4.10±0.64	4.09±0.65	0.94

Source: Authors

The results presented in Table 3 showed no statistically significant differences among stakeholder groups ($p > 0.05$), indicating broadly shared perceptions of the importance and developmental potential of thematic routes. Consequently, H1.2 was not supported.

The Kruskal–Wallis test was used to examine differences in attitudes according to educational level. Respondents with primary, secondary and higher education were compared. The results are shown in Table 4.

Table 4. The Kruskal – Wallis test – differences regarding education

Dimension	Primary (M ± SD)	Secondary (M ± SD)	Faculty (M ± SD)	p-value
Perception of the importance of theme routes	4.12 ± 0.78	4.20 ± 0.72	4.25 ± 0.68	0.312
Importance of natural resources and attractions	4.05 ± 0.81	4.18 ± 0.75	4.22 ± 0.70	0.289
Cultural - historical heritage	4.08 ± 0.79	4.15 ± 0.74	4.19 ± 0.71	0.274
Gastronomy and local tradition	4.02 ± 0.82	4.12 ± 0.77	4.18 ± 0.69	0.341
Interaction - infrastructure	4.00 ± 0.85	4.10 ± 0.78	4.15 ± 0.72	0.328
Sustainability and the role of the community	4.07 ± 0.80	4.14 ± 0.74	4.20 ± 0.70	0.301

Source: Authors

The results revealed no statistically significant differences according to educational level ($p > 0.05$), indicating similar perceptions of thematic routes among respondents with different educational backgrounds. Consequently, H1.3 was not supported.

Discussion

The findings indicate that respondents perceive thematic routes as a valuable instrument for enhancing the tourism offer of Šumadija and Pomoravlje. Positive attitudes were expressed toward their role in the valorization of natural resources, preservation of cultural heritage, promotion of gastronomy, infrastructure development, and community involvement. While the results support the general hypothesis (H1), sub-hypotheses H1.1, H1.2, and H1.3 were not confirmed, as no statistically significant differences were found according to gender, stakeholder status, or educational background. These findings reflect a broad consensus regarding the developmental potential of thematic routes rather than evidence of already achieved tourism benefits.

From a theoretical perspective, thematic routes represent integrated tourism products that connect natural, cultural, and local assets into coherent visitor experiences (Meyer, 2004; OECD, 2020). The results support previous studies emphasizing their contribution to destination competitiveness, identity building, and sustainable tourism development. Respondents particularly recognized the importance of natural resources, cultural heritage, gastronomy, and local traditions, confirming the relevance of these elements as the foundations of thematic route development (Butler, 2006; Timothy & Boyd, 2003; Hall & Sharples, 2003).

The findings also highlight the importance of accessibility, transport infrastructure, accommodation, and tourism integration. Strong support for road infrastructure and signage confirms that successful thematic routes depend not only on attractive resources but also on quality supporting services and effective stakeholder coordination. Although digital tools were viewed positively, respondents appeared to prioritize physical infrastructure and service quality, suggesting that technological solutions should complement rather than replace basic tourism requirements. This is consistent with previous research demonstrating the growing relevance of digital transformation and digital services across different sectors and stakeholder groups (Lukić Nikolić et al., 2026; Labus & Lukić Nikolić, 2024).

Sustainability emerged as another critical dimension. Respondents strongly supported the preservation of natural and cultural resources and emphasized that local communities should benefit from tourism development. These findings are consistent with sustainable tourism principles, which stress stakeholder participation, responsible governance, and the continuous monitoring of economic, social, and environmental impacts (UNWTO, 2013; OECD, 2020; Jaganjac et al., 2024).

From a project management perspective, the development of thematic routes requires a systematic approach that includes resource identification and evaluation, stakeholder engagement, route planning, allocation of responsibilities, financing mechanisms, and performance monitoring (PMI, 2021). Long-term success depends on cooperation among local authorities, tourism organizations, businesses, cultural institutions, and community representatives, as well as on the establishment of measurable indicators for evaluating tourism outcomes.

The development of thematic routes in Šumadija and Pomoravlje also depends on an adequate legal and institutional framework. Besides the availability of tourism resources, successful implementation requires compliance with the Hospitality Law (Official Gazette of the Republic of Serbia, 2019a), Tourism Law (Official Gazette of the Republic of Serbia, 2019b), Nature Protection Law (Official Gazette of the Republic of Serbia, 2021a), and Cultural Heritage Law (Official Gazette of the Republic of Serbia, 2021b). Routes involving protected natural areas or heritage sites must be planned in accordance with conservation requirements, institutional responsibilities, and site-specific regulations. Therefore, the legal framework should be viewed as an integral part of route planning rather than merely an administrative obligation.

Conclusion

This paper examined stakeholders' perceptions of thematic routes as a tool for sustainable tourism development in the Šumadija and Pomoravlje region. The results indicate a generally positive perception of thematic routes and their potential contribution to local economic development, heritage preservation, gastronomy promotion, and the integration of tourism resources into a competitive tourism offer.

Respondents particularly emphasized the importance of natural attractions, cultural and historical heritage, local gastronomy, infrastructure, and community participation as key elements of successful thematic routes. The results suggest that thematic routes can enhance destination attractiveness, diversify tourism products, and support sustainable regional development.

From a practical perspective, successful implementation requires adequate infrastructure, stakeholder cooperation, effective management structures, compliance with legal and heritage protection requirements, and continuous monitoring of tourism impacts. Project planning should therefore integrate tourism, conservation, and community-development objectives.

The study is limited by its reliance on self-reported perceptions and its focus on a single region, which restricts broader generalization of the findings. Future research should include larger samples, comparative regional studies, and objective performance indicators, such as visitor numbers, tourism expenditure, and local business revenues.

Overall, thematic routes represent a promising strategy for strengthening the tourism competitiveness of Šumadija and Pomoravlje. Their long-term success will depend on strategic planning, stakeholder collaboration, effective resource management, and adherence to legal and sustainability principles.

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Conflict of interests

The authors declare no conflict of interest.

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AGRICULTURAL AND RURAL DEVELOPMENT IN EU MEMBER STATES: A PRE- AND POST-COVID-19 ASSESSMENT

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ABSTRACT

The Covid-19 pandemic has tested the sustainability of the agricultural sector and rural areas of the European Union. Beyond the short-term responses of the member countries, the pandemic has raised the issue of redefining long-term development policies. The purpose of this paper is a comparative assessment of the agricultural and rural development of the European Union member states before and after the Covid-19 pandemic. Hierarchical and K-means cluster analysis are applied in the research. The study aims to evaluate the resilience of European Union member states to the Covid-19 pandemic and their heterogeneity by analysing changes in indicators of agricultural and rural development. The research results confirmed the resilience of most countries of the European Union, as well as the existence of specific patterns of their agricultural and rural development. These findings indicate that redefining agricultural and rural development policies still requires careful consideration of country-specific characteristics.

Introduction

The Covid-19 pandemic represented a strong external shock that emphasised the issue of sustainability of agricultural sector and rural development of the European Union (EU). In parallel, the scientific focus during the pandemic shifted from economic results

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to the resilience of agricultural and rural systems. Namely, in the era of deep socio-economic transformations, crisis periods, and environmental challenges, understanding the development dynamics of agricultural and rural areas requires a comprehensive, systemic approach that goes beyond traditional concepts focused solely on increasing productivity. On the other hand, the Covid-19 pandemic redefined the importance of rural areas as safer environments for both living and working and affirmed the question of their long-term revitalization, as a response to potential future crises among other things. The empirical picture of the European Union reveals that the short-term responses of the member states to the challenges of the Covid-19 pandemic were heterogeneous, while in parallel the countries made efforts to change the policies and approach to agricultural and rural development (Gonzales-Martinez et al., 2021; Stanišić et al., 2022; Daniłowska, 2024). In the years after the pandemic, the achieved results and indicators of agricultural and rural development represent an objective assessment of the success of the redefined policies.

A review of the literature on the effects of the Covid-19 pandemic on the agricultural and rural development of the EU member states concluded that the researchers' focus was primarily on the current resilience of the agricultural and rural sector and recommendations for redefining policies and strategies for future development. Also, there is a limited body of research that included the analysis of a large number of agricultural and rural development indicators, all the EU member countries or those that were conducted after the end of the Covid-19 pandemic. In accordance with this identified gap, the research objective was formulated. The aim of the paper is to assess the resilience of their agricultural and rural systems and the existence of specific patterns of agricultural and rural development of the EU member states in the year before and the year after the Covid-19 pandemic. Pre- and post-Covid-19 assessment implies a quantitative analysis of changes in indicators of agricultural and rural development of the EU member states in 2023 compared to 2019.

To achieve the defined research aim, this paper addresses the following research questions:

RQ1: Do the changes in agricultural and rural development indicators across the EU member states, comparing the year before and the year after the Covid-19 pandemic, indicate the resilience of the agricultural and rural sector?

RQ2: Is there heterogeneity among the EU member states regarding the dynamics of agricultural and rural development indicators when comparing the year before and the year after the Covid-19 pandemic?

The paper is organised into five sections. Following this introduction, a review of the literature on the impact of the Covid-19 pandemic on agricultural and rural development is given, both in general and in the context of the European Union. After that, the information base and methodological framework of the research are explained. The results of the cluster analysis and their discussion are the next segment of the paper, followed by concluding remarks.

Literature review

The Covid-19 pandemic was an external shock that tested the sustainability and resilience of agriculture, and indirectly rural development, through numerous restrictions, from movement restrictions to market and supply chain disruptions and labour availability. The impact of the Covid-19 pandemic on agriculture and rural development can be viewed through the prism of resilience theory. The way to do this is through assessment of the ability of agricultural and rural systems to absorb external shocks, to successfully adapt to changed conditions, to recover, and to progress despite crisis situations. At least for a short time, the pandemic shifted the focus away from agricultural productivity and economic outcomes. Instead, it highlighted the ways and relationships that enable agricultural systems to adapt to crisis events, evolve, and leverage unexpected circumstances (Darnhofer, 2021).

Empirical evidence of European agricultural systems has shown that resilience is multi-layered and dynamic in nature. The response of agricultural system actors was focused on immediate overcoming of problems, without considering long-term implications. Transformative capacities of European agricultural were not expressed and the crisis was not used as an opportunity to initiate significant structural reforms (Meuwissenet al., 2021). Also, empirical findings confirmed the lower resilience of large agricultural producers, due to less flexibility to adapt to drastically changed business conditions, while resilience increases with diversification and greater orientation towards the products that have added value (Guedegbe et al., 2023). The resilience of agricultural systems must be improved through technical, economic, social and institutional measures that mitigate disruptions caused by shocks such as the Covid-10 pandemic, primarily by ensuring the food security (Štreimikienė et al., 2022). Technical measures should provide adequate adaptive infrastructure capacities. Economic support from the state is also a desirable mechanism. The proactive engagement of the system's organisations and a resilient rural community are key drivers for the long-term social stability of the agricultural sector. Their inclusion is the basis of the social sustainability of agriculture (Krstić, 2018). Lioutas & Charatsari (2021), based on the lessons learned from the Covid-19 pandemic, propose the synergistic application of smart technologies and the introduction of community-based hybrid marketing models as key mechanisms for strengthening the resilience and transformative capacity of agriculture.

Agnoletti et al. (2020) observe the relationship between rural development and the Covid-19 pandemic in an inverse way, reaching and confirming empirically a conclusion about the importance of the revitalization of rural areas. The population's resistance to future health crises, as well as society's resistance to external shocks of a different nature, can be increased by the revitalization of rural areas and a more balanced relationship with nature. Consideration of the problem of resilience of rural areas to crises, including the Covid-19 pandemic, brought to the fore the role of local solutions and decisions. These solutions must be in line with the goals and interests of the community with its active participation. Diversification, local leadership, and trust in the local business community can significantly contribute to the reduction of tensions in times of crisis and the resilience

of rural areas. The Covid-19 pandemic has redefined the perception of rural areas as safer and more functional spaces for living and working. Future development of these areas must be based on intergenerational access, innovation, knowledge, entrepreneurship, and diversification of non-agricultural activities (Chigbu et al., 2021; Panić et al., 2024; Dimitrijević, 2025). In order to avoid long-term socioeconomic and ecological imbalances, many countries have realised that it is necessary to innovate development strategies. Their implementation should, through the creation of new sources of income, transform the village into a resilient and attractive entity with the same living conditions as those of the city. In the context of complementary agricultural and rural development, Gusmanov et al. (2023) argue that agricultural production is vital for rural sustainability during a pandemic. This stability can be achieved through effective producer support programs and by creating space for agribusiness localization.

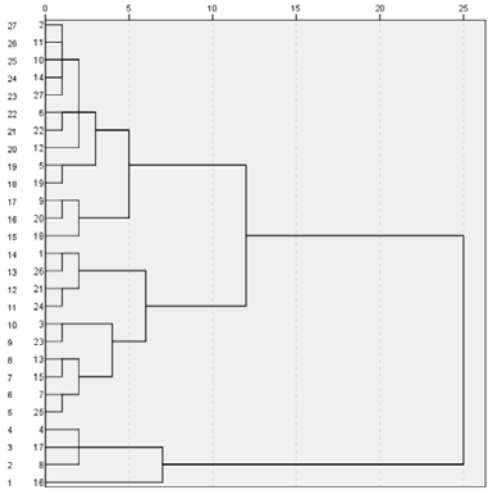
Research on the resilience of agriculture and rural areas to the Covid-19 pandemic within the European Union examines these issues from different perspectives. Gonzales-Martinez et al. (2021) confirmed that the European Union's agricultural sector proved highly resilient in the early stages of the Covid-19 pandemic and predicted that this trend would continue. In doing so, they conclude that the impact of the Covid-19 pandemic on food production varied across member states. The scale of this impact was directly dependent on the low elasticity of demand for food and supportive economic policy measures. Stanišić et al. (2022) investigate the impact of the Covid-19 pandemic on the economic performance of agriculture in the European countries in the initial year of the Covid-19 pandemic (2020) and conclude that the role of agriculture in contributing to key macroeconomic determinants at the country level has not changed. They note the differences between countries when it comes to the contribution of agriculture to the GDP during the Covid-19 pandemic, while the difference in the contribution to employment was not recorded. Through a comparative analysis of agricultural and rural development indicators from 2016 to 2023, Daniłowska (2024) confirmed that the Covid-19 pandemic caused a medium-term decline or slowdown in agricultural value-added growth across the six leading EU countries. This trend was accompanied by severe labour shortages as well as disruptions in both the livestock and crop sectors. The author concludes that there is a different intensity of the pandemic influence in the different analysed countries. Marcuță et al. (2021) explore the impact of the Covid-19 pandemic on food security as a key component of global, national, and human security. Their empirical analysis of key economic and agricultural indicators indicated that food supply stability within the European Union was preserved thanks to the high level of agricultural production development. At the same time, preserving the food supply chain was one of the key challenges and key tasks during the pandemic (Paraschivu & Cotuna, 2021). Through an empirical analysis conducted in the early stages of the Covid-19 pandemic, from March to June 2020, Matthews (2020) reaches similar results. The author points to a high degree of resilience within the EU food system, as farmers, processors, and traders successfully maintained supply continuity and adapted to structural changes in demand.

Materials and methods

The indicators included in the analysis are those defined and measured by the World Bank, expressed in relative values for the purpose of comparability. The difference in the values of the following indicators in the year after (2023) compared to the year before the Covid-19 pandemic (2019) represents the informational basis of the research: Agricultural raw materials exports (% of merchandise exports), Agricultural raw materials imports (% of merchandise imports), Employment in agriculture (% of total employment), Employment in agriculture, male (% of male employment), Employment in agriculture, female (% of female employment), Agriculture, forestry, and fishing, value added (% of GDP), and Rural population (% of total population) (World Bank, 2000; World Bank, 2026).

Hierarchical and K-means cluster analysis were applied in the paper. When determining the number of clusters, the possibility of a three-cluster, four-cluster, and five-cluster solution was considered. Based on the results of the hierarchical cluster analysis, utilising Ward's method and squared Euclidean distance, a decision was made to retain the three-cluster solution. The analysis of the agglomeration schedule showed a sudden jump in the value of the coefficients in the penultimate steps of the merger (from 93.15 to 121.98, and then to 182.00), which indicates the merger of mutually heterogeneous groups. This solution was fully confirmed by a visual inspection of the dendrogram, where three primary, stable branches can be clearly observed by cutting the scale of the rescaled distance at 12 (Figure 1).

Figure 1. Dendogram



Source: Author's calculation based on SPSS 25.0

K-means cluster analysis was applied in order to group the EU member states according to changes in the value of agricultural and rural development indicators in the year after compared to the year before the Covid-19 pandemic. Statistical significance of the difference between the defined clusters was examined by analysis of variance.

Results and discussions

Table 1 shows the final cluster centres and the characteristics of the three defined clusters. Cluster 1 includes countries with the largest negative changes in all observed indicators of agricultural and rural development. Negative changes in the export of agricultural raw materials, employment in agriculture, and the share of the rural population in the total were particularly pronounced. Cluster 2 stands out as the cluster with the most stable performance. It is characterised by values close to zero or positive values for certain indicators. Positive changes in the value of the indicators were recorded for total employment in agriculture, male employment in agriculture, and the share of value added of agriculture, forestry, and fishing in GDP. This indicates relative stability or an increase in the value of these indicators in 2023 compared to 2019. At the same time, the recorded change in the share of the rural population in the total population indicates its decrease in 2023 compared to 2019. Based on this, it can be concluded that changes in employment and the economic role of agriculture do not have to move in the same intensity and direction as changes in the rural demographic structure. This cluster, therefore, includes countries where changes were not equally pronounced in all dimensions of rural and agricultural development. The third cluster is characterised by negative changes in the values of most indicators, but they are less pronounced in some indicators than in the first cluster. At the same time, this is the only cluster where there is a positive change in the share of the rural population in the total. This once again confirms that negative changes in the economic indicators of agricultural and rural development do not necessarily have to be accompanied by a decrease in the share of the rural population.

Table 1. Final Cluster Centres

Indicator	Cluster		
	1	2	3
Agricultural raw materials exports (% of merchandise exports)	-1.00	-0.27	-0.20
Agricultural raw materials imports (% of merchandise imports)	-0.52	-0.17	-0.26
Employment in agriculture (% of total employment)	-1.14	0.03	-0.43
Employment in agriculture, male (% of male employment)	-1.49	0.12	-0.36
Employment in agriculture, female (% of female employment)	-0.76	-0.07	-0.48
Agriculture, forestry, and fishing, value added (% of GDP)	-0.32	0.02	-0.21
Rural population (% of total population)	-0.92	-0.69	0.07

Source: Author's calculation based on SPSS 25.0

The membership of European Union member states in the defined clusters is shown in Table 2. Four countries belong to Cluster 1, which was identified as the cluster with the largest negative changes in the values of the observed indicators, 14 countries belong to Cluster 2, as the cluster with the most stable values of the observed indicators, while

9 countries belong to Cluster 3, as the cluster with moderate changes in the values of the observed indicators.

Table 2. Cluster membership

Country	Cluster	Distance	Country	Cluster	Distance	Country	Cluster	Distance
Austria	2	1.024	France	2	0.773	Malta	2	0.618
Belgium	2	0.298	Germany	2	0.322	Netherlands	2	0.855
Bulgaria	3	0.581	Greece	2	0.997	Poland	3	0.846
Croatia	1	0.657	Hungary	3	0.332	Portugal	2	0.736
Cyprus	3	1.035	Ireland	2	0.456	Romania	3	1.320
Czechia	2	0.890	Italy	3	0.453	Slovak Republic	3	0.749
Denmark	2	0.841	Latvia	1	1.329	Slovenia	3	0.608
Estonia	1	0.783	Lithuania	1	1.010	Spain	3	0.800
Finland	2	0.682	Luxembourg	2	1.015	Sweden	2	0.339

Source: Author's calculation based on SPSS 25.0

The belonging of Croatia, Estonia, Latvia and Lithuania to Cluster 1 as the cluster that recorded the largest negative changes in agricultural and rural development indicators can be attributed to the less favorable structural characteristics of its agricultural sector, dependence on imported raw materials in production and, in the case of the aforementioned Baltic countries, a lower level of economic development heavily reliant on the primary sector (Jurjević et al., 2023; Marković & Marjanović, 2025). The structural problem and the extinction of property in Croatia or the lower technical equipment of agriculture in the Baltic countries made them more vulnerable to the consequences of the crisis caused by the Covid-19 pandemic. Economic results and incomes in Croatian agriculture are still below the EU average. Croatia records a deficit in the trade exchange of agricultural products, and there are also numerous obstacles to the application of innovations in this sector (OECD, 2025).

More than half of the EU member states belong to cluster 2 as a cluster with stable performance. Changes in the value of certain indicators in this cluster, such as employment and value added, are even positive in the year after the pandemic compared to the year before the Covid-19 pandemic. This can be attributed to the development of countries, a high level of modernization of agricultural production and digitalization, larger capital-intensive farms and high labor productivity (Marcuță et al., 2021; Herman, 2025).

Cluster 3, in addition to the countries of Central and Eastern Europe, also includes two countries of Southern Europe (Italy, Spain, and Cyprus). Their location in the group of countries with moderate, but predominantly negative changes in indicators of agricultural and rural development can be explained, among other things, by the dependence of agriculture and tourism and their exposure to a double shock during the period of the Covid-19 pandemic, as well as the pronounced and parallel impact of climate change (Jiménez-Donaire et al., 2020; Coderoni & Pagliacci, 2023). The moderate negative changes can be attributed to the diversified structure of agriculture, which proved to be more resistant to shocks.

The results of the analysis of variance (ANOVA), which evaluated the statistical significance of cross-cluster differences, are shown in Table 3. The grouping of the EU member states is similar to the results of research of Herman (2024), which applied multivariate analysis to group them according to socio-economic indicators of agriculture. In this research, the new EU member states and the former central-planned economies are grouped in separate and lower-performing clusters than those in which the developed countries of Western and Northern Europe were located. Filipović et al. (2025) identify most of the countries that belong to Cluster 2 in this study as countries oriented towards sustainable agricultural production.

Table 3. ANOVA

		Sum of Squares	df	Mean Square	F	Sig.
Agricultural raw materials exports (% of merchandise exports)	Between Groups	1.991	2	0.995	9.391	0.001
	Within Groups	2.544	24	0.106		
	Total	4.535	26			
Agricultural raw materials imports (% of merchandise imports)	Between Groups	0.368	2	0.184	5.872	0.008
	Within Groups	0.752	24	0.031		
	Total	1.121	26			
Employment in agriculture (% of total employment)	Between Groups	4.464	2	2.232	33.526	0.000
	Within Groups	1.598	24	0.067		
	Total	6.062	26			
Employment in agriculture, male (% of male employment)	Between Groups	8.173	2	4.086	27.187	0.000
	Within Groups	3.607	24	0.150		
	Total	11.780	26			
Employment in agriculture, female (% of female employment)	Between Groups	1.840	2	0.920	14.634	0.000
	Within Groups	1.509	24	0.063		
	Total	3.349	26			
Agriculture, forestry, and fishing, value added (% of GDP)	Between Groups	0.497	2	0.249	2.143	0.139
	Within Groups	2.786	24	0.116		
	Total	3.283	26			
Rural population (% of total population)	Between Groups	4.095	2	2.047	10.702	0.000
	Within Groups	4.591	24	0.191		
	Total	8.686	26			

Source: Author's calculation based on SPSS 25.0

The results of the analysis of variance indicate the existence of statistically significant differences between the three clusters of European Union countries in terms of changes in most of the observed indicators in 2023 compared to 2019. Statistically significant differences are found in six of the seven analysed indicators, where the most pronounced differences are recorded in the share of employment in agriculture in total employment ($F = 33.326$; $p < 0.001$), as well as in the share of men employed in agriculture in total men employment ($F = 27.187$; $p < 0.001$). Statistically significant differences in changes in the value of indicators are also recorded in the employment of women in agriculture, the share of the rural population in the total population, as well as the share of agricultural raw materials in merchandise exports and imports. In contrast, there are no statistically significant differences between the clusters when it comes to the

changing share of agriculture, forestry and fishing value added in the GDP ($F = 2.143$; $p = 0.139$). Therefore, the formed groups of countries differ according to the patterns of changes in most of the observed structural indicators, while the differences in the change in the contribution of agriculture, forestry and fishing to the creation of GDP cannot be statistically confirmed at the 5% significance level.

Conclusions

The agriculture and food industry sector in the European Union showed a high degree of resilience during the Covid-19 pandemic. Macroeconomic shocks have had a limited long-term impact on overall supply and consumption. However, the crisis has exposed vulnerabilities in terms of temporary access to food due to reduced imports, labour shortages, and disruptions in supply chains for specific sectors. This required quick and short-term responses from the EU member states that differed from country to country. In this context, the aim of the research was to analyse the indicators of agricultural and rural development and their dynamics to confirm the resilience and heterogeneity of the EU member states in the context of the impact of the Covid-19 pandemic on the agricultural and rural sector. By applying cluster analysis, the EU member states are grouped into three clusters depending on the change in the value of the analysed indicators of agricultural and rural development in the year after compared to the year before the Covid-19 pandemic.

The results of the cluster analysis showed that more than half of the EU member states are in Cluster 2, which was singled out as a cluster with stable performance. A total of 9 countries belong to Cluster 3, characterised by minimal negative changes in the analysed indicators, while only four countries are in Cluster 1, characterised by somewhat larger negative changes in the analysed indicators. As the majority of EU member states belong to the second or third cluster, it can be concluded about a positive answer to the first research question. The values of indicators of agricultural and rural development in the year after the Covid-19 pandemic, compared to the year before, confirmed the resilience of the agricultural and rural sectors of the European Union. The analysis of variance confirmed a statistically significant difference between the formed clusters when it comes to 6 out of 7 analysed indicators. Statistically significant differences between clusters were recorded in terms of changes in import and export of agricultural raw materials, employment in agriculture and rural population, while there are no statistically significant differences between clusters when it comes to changes in the share of agriculture, forestry, and fishing value added in the GDP. It can be concluded that there is still a certain heterogeneity among the EU member states regarding the dynamics of agricultural and rural development indicators when comparing the year before and the year after the Covid-19 pandemic. This heterogeneity can be explained by different levels of economic development of countries, different structural characteristics of agriculture, different levels of modernization and digitization of agricultural production or exposure to climate change.

The limitation of the research is reflected in the fact that it is impossible to statistically completely isolate the percentage of the change in the value of the indicator that can be attributed to the Covid-19 pandemic, and which to another geopolitical shock (the war in Ukraine) or to changes in the common agricultural policy that were instigated under the influence of the pandemic. As a direct response, the European Union has integrated recovery mechanisms into its common agricultural policy to strengthen the sustainability and digital and green transition of rural areas. Although the choice of 2023 as the year of analysis can partially separate these impacts, future research can be aimed at evaluating the changes caused by the joint impact of the aforementioned crises and the redefined political responses of the European Union in the context of agricultural and rural development.

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Conflict of interests

The authors declare no conflict of interest.

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ORGANISATIONAL AND ECONOMIC INDICATORS OF GRAPE PRODUCTION: THE CASE OF THE SERBIAN AUTOCHTHONOUS GRAPEVINE VARIETY PROKUPAC

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ABSTRACT

Improvements in the quality of Serbian wines and the growing recognition of the domestic wine sector have created more favourable conditions for investment in new vineyards. The economic sustainability of grape production depends on suitable production conditions, while increasing attention is given to autochthonous varieties, particularly Prokupac, which is used to produce red and rosé wines. This study analyses the organisational and economic indicators of Prokupac grape production and evaluates the economic feasibility of establishing new vineyards. Based on field data collected in the Šumadija wine-growing region (PDO), the analysis uses a technological production chart, analytical cost calculation, and three dynamic investment appraisal methods: Net Present Value (NPV), Internal Rate of Return (IRR) and Dynamic Payback Period (DPP). The results show a positive financial result of EUR 2,727.52/ha, with labour accounting for 50.06% of production costs. The investment indicators suggest economic feasibility under the assumed conditions.

Introduction

Viticulture has a long tradition in the Republic of Serbia and represents a very important branch of agriculture. The success of grape production depends on numerous factors, primarily natural conditions (climate, soil, etc.), but also organisational and economic factors (Dimitrijević et al., 2018). Investments in vineyard establishment

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require substantial financial resources, while the investment payback period may be considerably longer compared to some other perennial plantations (Sredojević et al., 2015; Petrović et al., 2025). Due to the specific characteristics of grape production, particularly the production conditions that vary considerably between different regions, production costs, labour organisation and investments in the establishment of new vineyards may also differ significantly (Stevanović et al., 2018; Schwerz et al., 2023). For these reasons, it is necessary to examine the organisational and economic indicators of grape production.

Regarding global grape production, it is noticeable that the total area under vineyards has gradually declined in recent years. The tendency for the reduction in vineyards has been identified within the last ten years. Based on the numbers provided by the International Organisation of Vine and Wine (OIV), the global area of vineyards stood at 7.09 million hectares in 2024. In comparison with 2020, it has decreased by 4.05%, and in contrast with 2015 by 4.76%. Even though the area under cultivation of grapes has been declining, the total grape production has been quite steady. Total grape production in 2024 was 77.73 million tonnes, representing about 0.7% more compared to 2015 (OIV, 2025). The major producers of grapes in the world include China (producing 17 million tonnes), Italy (with 7.3 million tonnes), and USA (producing 6.4 million tonnes) (OIV, 2025). Out of the total grape production across the world in 2024, about 47% was used in the production of wine and grape must and juice. The rest of the grape quantity was used for different purposes, out of which 46% was used as fresh grapes, while 7% of the grapes were used for the production of raisins (OIV, 2025; Agulheiro-Santos et al., 2021). However, in Europe, the majority of grapes harvested are used for wine-making purposes, whereas in Asia, the harvest of table grapes and grapes to be dried takes place much more often. It is these diverse uses that explain the significance of grapes as the raw material used in the food processing industry, the importance of grape production going far beyond agriculture (Alston & Sambucci, 2019).

These developments point to an increasing role of productivity and efficient land use in contemporary grape cultivation, leading to increased yield (Ohana-Levi & Netzer, 2025). However, at the same time, fluctuations in prices were registered over the period under analysis, as the prices of energy and mineral fertilizers went up. The biggest rise in the prices of inputs and thus costs of grape cultivation occurred in 2020-2022 and was associated with market disruptions because of the COVID-19 pandemic and military conflict around the globe (Ben Hassen & El Bilali, 2022; Belewu et al., 2024). Moreover, impacts of climate change in the form of drought are likely to further raise the prices of agricultural and food products (Accetturo & Alpino, 2023; Oo, 2026). At the same time, disturbances in international supply chains were noticed, leading to increased costs of agricultural production (Bodnár & Schuler, 2022; Kuik et al., 2024). It is necessary to point out that the impact of individual factors mentioned above was not estimated separately in this research, and the factor, which impacted the changes on the market the most, was not defined. Due to the mentioned market changes, the overall value of global grape production also increased (Table 1).

Table 1. Global value of grapes production (billion USD, current prices)

Element/year	2015	2016	2017	2018	2019	2020
Value	64.67	64.36	69.10	73.23	74.51	81.99
Element/year	2021	2022	2023	2024	Average	
Value	84.79	81.99	103.58	97.30	79.55	

Source: FAOSTAT, 2026.

Regarding the viticulture sector in the Republic of Serbia, it has undergone significant structural changes over a long period. These changes are primarily reflected in the reduction of vineyard areas and the number of agricultural holdings engaged in grape production. In 2023, the total area under vineyards in the Republic of Serbia decreased by 17.8% compared to 2012, while the number of agricultural holdings engaged in grape production declined by approximately 34.6% (SORS, Census of Agriculture, 2024). The same census also shows that the average vineyard area per agricultural holding increased from approximately 0.28 ha to 0.35 ha, which still represents a relatively small landholding (Ivanišević et al., 2015; SORS, 2024). According to available data from the Statistical Office of the Republic of Serbia, the productive vineyard area in 2025 amounted to 17,437 ha, while total grape production reached 140,718 tonnes, with an average yield of 8.1 t/ha. In 2024, total grape production amounted to 129,739 tonnes, with 17,719 ha of productive vineyards and an average yield of 7.3 t/ha. Accordingly, grape production increased by approximately 8.5% in 2025, despite a slight reduction in the productive vineyard area (SORS, 2026).

There are 22 wine-growing region identified in the Republic of Serbia, among them, there is the Šumadija wine-growing region (Protected Designation of Origin - PDO) which includes the territory of the area where the surveyed producers are situated. Šumadija wine-growing region was chosen as the research area since the production of grapes has a long tradition in this region, which also possesses the favourable natural conditions for the cultivation of grapes. According to the Census of Agriculture (SORS, 2013), the Šumadija wine-growing region included 1,119.79 ha of vineyards and approximately 5,000 agricultural enterprises, of which most were engaged in the cultivation of grapes for winemaking purposes. The municipality of Topola belonging to the Oplenac wine-growing subregion possessed the largest area of vineyards (Jakšić, 2014). According to the Census of Agriculture (SORS, 2024), Topola Municipality had the largest number of agricultural holdings with vineyards (781), followed by Kragujevac. Furthermore, the Šumadija wine-growing region has a relatively large number of wineries which play an important role in the purchase of grapes from local producers. Some of the developments that have occurred in recent years include the creation of new vineyards, better quality plant material, the use of mechanized operations, and improvements to the training of the vines on the trellis system. These changes are associated with a growing focus on the production of higher-quality grapes and wines (Jakšić et al., 2023). These developments also help explain why increasing attention has been paid to the promotion of wines produced from local and autochthonous grapevine varieties in Serbia in recent years. In the long term, increasing the area under vineyards planted with autochthonous

grapevine varieties, as well as producing wines from these varieties, may contribute to greater market recognition and improved competitiveness of domestic grape and wine producers (Petrović et al., 2024; Tello et al., 2024; Jeločnik et al., 2024a).

In addition to natural conditions, socio-economic factors may also have a significant influence on business performance in grape production. These primarily include the size of farms, labour availability, the level of mechanisation, access to processing facilities and distance from markets (Gogić, 2010a). Other factors that may also have an influence include input procurement conditions, agricultural policy measures and the availability of financing sources. Furthermore, organisational factors may also affect business performance, as they provide the basis for efficient and economically viable production (Kalanović et al., 2007). To ensure such production, farm managers and decision-makers must organise and carry out all production operations in a timely manner, while ensuring sufficient labour and the necessary production inputs (Dimitrijević et al., 2019; McCorkle et al., 2019). All these factors must be analysed when making decisions about investments in vineyard establishment, as the economic benefits are realised over a long period (Kalanović Bulatović & Milić, 2014; Signorini et al., 2022; Tingey-Holyoak et al., 2024). Research conducted in Serbia indicates that subsidies can significantly influence the economic efficiency of vineyard establishment and facilitate the financing of investments on agricultural holdings (Vasiljević et al., 2017). In addition, well-developed processing facilities and opportunities to combine grape production with winemaking enable the creation of added value and may positively influence the economic sustainability of production (Jeločnik et al., 2024b). Therefore, a comprehensive analysis of work organisation, production costs and required investment expenditure is necessary to assess the economic viability of grape production. Based on the above, the main objective of this research is to analyse the organisational and economic indicators of Prokupac grape production. Particular attention will be given to work organisation, production costs and investment assessment, as well as determining the economic feasibility of establishing new vineyards planted with this autochthonous grapevine variety. The obtained results may provide useful information for grape growers, wine producers and agricultural policymakers, contributing to investment decisions based on relevant data and the long-term economic sustainability of production.

Materials and Methods

For this study, data was gathered using surveys and interviews with grape growers from the Šumadija wine-growing region (PDO). Production conditions for the companies were very similar, and the expected period of vineyard exploitation was set at 40 years. After the vineyard entered into full production, grape yield and selling price, as well as costs of production, were supposed to stay at the same level until the 35th year of vineyard exploitation, when the yield would begin to decrease. With regard to the residual value of the vineyard in the final year of vineyard exploitation, it was assumed that the value of physical assets would be very small, while the residual value

of the investment would be equal to the total working capital invested. The value of the permanent working capital at the end of the year of vineyards' use was taken into account as cash flow. One should add that all calculations were done without any support, meaning that all investments would have been covered by the producer's own money. Moreover, one should say that all calculations are concerned with grapes meant for the production of high quality wine, including geographically identified ones, and hence, their yield is rather low but the price is higher. However, the calculations are concerned only with the production of grapes and possible earnings connected with it, but not with winemaking or geographically indicated products. Acquisition cost of the land was not considered while calculating the investments. Additionally, irrigation system, anti-hail nets and other investments were not included in the calculations since the surveyed producers do not use them. The surveyed producers generally do not insure their grape production or vineyards, which may, to some extent, affect certain economic indicators, particularly considering the increasingly pronounced impacts of climate change, as agricultural insurance may help mitigate the associated risks (Petrović et al., 2020). It is also important to note that producers have sufficient access to both family and hired labour and use their own agricultural machinery. The analytical cost calculation also included the costs of family labour, determined on the basis of total annual labour input, expressed in working days, with family labour valued at the same wage rate as hired (paid) labour. The costs of using the producers' own agricultural machinery included fuel, maintenance, and depreciation costs.

The methodology involved the development of a technological production chart covering all agricultural operations performed during the regular production cycle, as well as an analytical calculation of production costs. These calculations provided the basis for estimating investment expenditure and applying dynamic methods to appraise investments in the establishment of perennial plantations (Gogić, 2014; Ivanović & Marković, 2018; Ivanović & Todorović, 2024). The following dynamic methods were applied to assess investment efficiency: Net Present Value (NPV), Internal Rate of Return (IRR), and Dynamic Payback Period (DPP). The calculations were based on the assumption that the investment assessment is performed at the beginning of vineyard establishment. The analysis covered the entire 40-year vineyard exploitation period, allowing investment costs and benefits to be assessed over the productive lifespan of the vineyard. The total investment required to establish 1 ha of vineyard with the Prokupac grapevine variety was determined as the sum of investments in fixed capital and permanent working capital. The required permanent working capital was calculated based on annual production costs, the period during which funds are tied up, and the corresponding turnover ratios, following the methodology of Gogić (2014). Alternatively, the required investment in permanent working capital can be estimated by assuming that it amounts to 10% of the investment in fixed assets, or 20% in the case of investments in perennial plantations. However, a more detailed calculation methodology was applied in this study, allowing for a more precise determination of the required investment in permanent working capital by taking into account the specific characteristics of the

production process, the period during which funds are tied up, and the corresponding turnover ratios. Investment in fixed capital was determined based on the costs incurred during the vineyard establishment period (from Year 0 to Year 3), capitalised at an annual intercalary interest rate of 2.75% to account for the opportunity cost of using the producer's own financial resources. The net value of production generated in Year 3, after deducting harvesting and transportation costs, was offset against the calculated investment costs, thereby covering most of the costs incurred in that year. Year 3 marks the end of the investment period, as the vineyard reaches full production capacity in Year 4, when the value of production exceeds total production costs. Static methods of investment assessment were not applied due to the long exploitation period of vineyards. It is also important to emphasise the specific characteristics of grape production when analysing these indicators, particularly the fact that grape yields are absent or very limited during the initial years of vineyard exploitation, while certain production costs are still incurred (Gogić, 2010b; Carbone et al., 2019). All calculations and data were expressed per hectare of vineyard, while monetary values were presented in euros (EUR), using an exchange rate of 1 EUR = 117.3652 RSD.

The results of the research provide information to support decision-making regarding investments in the establishment of new vineyards, as well as the identification of key factors that may influence the achievement of positive business performance in grape production. Potential research limitations primarily relate to the use of data collected from only one wine-growing region, although the proposed analytical model can be applied to any other wine-growing region. Another limitation concerns the assumption that grape prices and production costs remain constant throughout the observed period. This is particularly relevant considering global changes in agricultural and food commodity prices, as well as the increasing promotion of wines produced from the autochthonous Prokupac grapevine variety, which may lead to higher market prices for grapes of this variety. Furthermore, the exclusion of subsidies and other forms of financial support from the calculations represents an additional limitation, as access to such support could significantly improve both business performance indicators and the economic efficiency of the investment compared with the obtained results. Lastly, the outcome of the research can be influenced by the wine-growing zone where production occurs, the methods used during production, the type of grapevine used, how the investment is financed, the qualification for subsidies and other incentives, among others.

Results and Discussion

Technological production chart embraces all agricultural operations carried out during one cycle of production and the frequency of their execution, labour input and agricultural machinery used. Moreover, the technological chart takes into account work performance indicators including the precise time needed for performing each particular operation. It provides an opportunity for deeper analysis of the technological and organisational requirements of production and helps to obtain the indicators serving as a basis for analysis of production costs and then estimation of economic efficiency of

investments in the establishment of the vineyard. The interviewed producers have the required agricultural machinery and enough number of labour force, both family and hired one, that allows carrying out all the operations timely. These conditions create the basis for successful production of grapes. The average density of planting is 4,400 vines per hectare, which was taken as a basis for cost calculation and investment analysis. In addition, the grape yield was limited to provide production of high-quality grapes and its average yield per the interviewed producers is 9,645.25 kg/ha that corresponds to approximately 2.2 kg per vine.

Table 2. Schedule of Vineyard Operations and Input Requirements for Prokupac Grape Production (1 ha)

Operation	Timing	Extent	Workers	Labour (worker-days/ha)	Labour (h/ha)	Machinery (h/ha)
Mechanical pre-pruning	Jan–Feb	1 pass	1	0.48	4.76	4.76
Manual winter pruning	Jan–Feb	1 pass	1	9.09	90.91	–
Shredding of prunings	Feb	1 pass	1	0.18	1.82	1.82
Replacement of posts and wire tensioning	Mar	1 pass	2	3.08	30.77	–
Cane bending and tying	Mar	1 pass	1	4.17	41.67	–
Shallow soil cultivation	Mar–Apr	1 pass	1	0.16	1.64	1.64
Plant-protection spraying	Apr	1 pass	1	0.21	2.08	2.08
Loading, transport and unloading of mineral fertiliser	Apr	0.25 t	3	0.05	0.50	0.17
Loading and spreading of mineral fertiliser	Apr	1 pass	1	0.16	1.63	1.63
Inter-row mowing	May	1 pass	1	0.15	1.54	1.54
Shallow soil cultivation	May	1 pass	1	0.20	1.95	1.95
Shoot thinning	May	1 pass	1	5.88	58.82	–
Shoot positioning in trellis	May	1 pass	1	4.00	40.00	–
Plant-protection spraying	May	2 passes	1	0.42	4.17	4.17
Shoot thinning	Jun	1 pass	1	5.00	50.00	–
Mechanical green pruning	Jun	1 pass	1	0.48	4.76	4.76
Plant-protection spraying	Jun	3 passes	1	0.62	6.25	6.25
Shallow soil cultivation	Jun	1 pass	1	0.20	1.95	1.95
Inter-row mowing	Jul	1 pass	1	0.15	1.54	1.54
Lateral shoot tipping	Jul	1 pass	1	5.00	50.00	–
Plant-protection spraying	Jul	2 passes	1	0.42	4.17	4.17
Manual leaf removal	Jul	1 pass	1	5.00	50.00	–
Inter-row mowing	Aug	1 pass	1	0.15	1.54	1.54
Cluster thinning	Aug	1 pass	1	6.67	66.67	–
Plant-protection spraying	Aug	1 pass	1	0.21	2.08	2.08
Manual leaf removal	Sep	1 pass	1	2.86	28.57	–
Loading, transport and unloading of crates	Sep–Oct	960 crates	3	0.58	5.76	1.92
Manual grape harvesting	Sep–Oct	9.6 t	1	21.33	213.33	–

Operation	Timing	Extent	Workers	Labour (worker-days/ha)	Labour (h/ha)	Machinery (h/ha)
Loading and transport of grapes	Sep–Oct	9.6 t	3	1.44	14.40	4.80
Shallow soil cultivation	Oct–Nov	1 pass	1	0.16	1.64	1.64
Total annual requirements	—	**30 operations**	—	**78.49**	**784.92**	**50.40**

Source: Authors' calculations based on collected data.

Based on these data presented in Table 2, farm owners can calculate and estimate the number of workers required to perform specific agricultural operations, taking into account the total working time needed for each operation. It can be concluded that grape production of the Prokupac variety is highly labour-intensive, requiring a total of 784.92 labour hours per production cycle (equivalent to 78.49 working days, assuming a 10-hour working day), while machinery use amounts to 50.40 working hours annually. Grapevine protection was among the most frequently performed operations, with an average of nine applications per year during the period analysed. Considerable labour input is also required for operations such as manual pruning, defoliation, yield reduction, and grape harvesting, with one worker able to harvest approximately 450 kg of grapes per day. Based on the presented data, calculations of production input, labour, and agricultural machinery costs were performed, and the corresponding results are presented in Table 3. The organisational indicators of grape production provide the basis for the analytical calculation of production costs, as well as for decision-making related to the planning and initiation of grape production activities. Furthermore, determining the structure and level of production costs enables an assessment of the economic performance of grape production, while the obtained data also provide an important basis for investment calculations and the projection of future cash flows. In this way, a link is established between the technological and organisational characteristics of production and the economic evaluation of investments in vineyard establishment.

Table 3. Analytical Calculation of Prokupac Grape Production (EUR/ha)

Indicator / cost item	Value	Share (%)
1. Grape yield (kg/ha)	9,645.25	–
2. Selling price (EUR/kg)	0.85	–
I Production value (1 × 2)	**8,198.46**	–
II Direct materials (3+4+5)	**910.60**	**16.64**
3. Mineral fertilisers	213.20	3.90
4. Plant-protection products	618.30	11.30
5. Other consumable materials	79.10	1.45
III Mechanisation and production services	**736.57**	**13.46**
6. Own machinery	736.57	13.46
IV Vineyard depreciation	**618.63**	**11.31**
V Direct labour (gross wages) (7+8)	**2,738.80**	**50.06**
7. Permanent labour	1,078.27	19.71

Indicator / cost item	Value	Share (%)
8. Seasonal labour	1,660.53	30.35
VI Other direct overheads	**36.86**	**0.67**
VII Financing costs (9+10)	**409.48**	**7.48**
9. Interest on fixed capital	351.35	6.42
10. Interest on permanent working capital	58.13	1.06
VIII Marketing and selling costs	**20.00**	**0.37**
IX Total production costs including selling (II+III+IV+V+VI+VII+VIII)	**5,470.94**	**100.00**
Unit cost of grapes (EUR/kg)	0.57	–
X Financial result (I-IX)	**2,727.52**	**–**

Source: Authors' calculations based on collected data.

The calculation of revenues and costs associated with Prokupac grape production per hectare provided the basis for the analytical production calculation presented in Table 3. The average grape yield amounted to 9,645.25 kg/ha, which, at an average selling price of 0.85 EUR/kg, resulted in a total production value of 8,198.46 EUR/ha. Regarding production costs, total costs amounted to 5,470.94 EUR/ha, with labour costs accounting for the largest share of total production costs, at 50.06% (2,738.80 EUR/ha). This finding further confirms the importance of the data presented in Table 2, highlighting that efficient work organisation and labour requirement planning can significantly influence the economic performance of grape production. In terms of cost structure, direct material costs (mineral fertilisers, plant protection products, and other auxiliary materials) represented the second-largest component, accounting for 16.64% of total production costs, followed by machinery costs, with a share of 13.46%. The financial results, calculated as the difference between total production value and total production costs, amounted to 2,727.52 EUR/ha, while the calculated unit cost of grape production was 0.57 EUR/kg. These data provide the basis for further analyses related to investment calculations and the assessment of the economic feasibility of investments.

Table 4. Calculation of Permanent Working Capital Requirements for Prokupac Grape Production (EUR/ha)

Component	Annual base	Days tied up	Turnover ratio	Capital required
Gross operating-capital requirement	5,412.81	304	1.20	4,510.68
Trade payables: materials and services	1,647.17	17	21.50	76.61
Vineyard depreciation	618.63	30	12.17	50.83
Accrued gross wages	2,738.80	30	12.17	225.05
Other liabilities, taxes and fixed-capital interest	388.21	30	12.17	31.90
Other operating liabilities	20.00	30	12.17	1.64
Total short-term operating financing	**5,412.81**	**—**	**—**	**386.03**
Permanent working-capital investment	**—**	**—**	**—**	**4,124.64**

Source: Authors' calculations based on collected data (following Gogić, 2014).

Table 4 presents the calculation of the required investment in permanent working capital for Prokupac grape production on an area of 1 ha. The required investment was determined by taking into account the specific characteristics of the production process, the period during which funds are tied up, and the corresponding turnover ratios. The estimated permanent working capital requirement of 4,124.64 EUR represents an integral component of total investment expenditures, which, in addition to working capital, include direct investments in vineyard establishment on an area of 1 ha. Given the long vineyard exploitation period (40 years), it was assumed that the residual value of the vineyard at the end of its productive lifespan would be negligible and that the terminal value of the investment would be equal to the total amount of the initial investment in permanent working capital. Accordingly, in the final year of vineyard exploitation, the value of production is increased by the amount of invested permanent working capital, which is recorded in the investment calculation as the residual value of the investment.

Table 5. Investment Costs for Prokupac Vineyard Establishment by Year (EUR/ha)

Cost component	Year 0	Year 1	Year 2	Year 3	Total
Labour	2,000.00	800.00	2,250.00	900.00	5,950.00
Tractor and machinery operations	2,250.00	290.00	630.00	250.00	3,420.00
Vineyard Design	550.00	–	–	–	550.00
Grapevine Planting Material	5,810.00	–	–	–	5,810.00
Replacement vines	–	720.00	–	–	720.00
Vineyard Trellis Materials	–	–	7,100.00	–	7,100.00
Production Inputs	370.00	300.00	330.00	590.00	1,590.00
Total establishment costs	**10,980.00**	**2,110.00**	**10,310.00**	**1,740.00**	**25,140.00**

Source: Authors' calculations based on collected data.

Table 6. Net Fixed-Capital for Prokupac Vineyard Establishment (EUR/ha)

Year	Nominal outlay	Compound factor*	Capitalised outlay	Production offset	Net fixed capital
0	10,980.00	1.08479	11,910.99	–	11,910.99
1	2,110.00	1.05576	2,227.65	–	2,227.65
2	10,310.00	1.02750	10,593.53	–	10,593.53
3	1,740.00	1.00000	1,740.00	1,542.50	197.50
Total	**25,140.00**	**—**	**26,472.16**	**1,542.50**	**24,929.66**

Source: Authors' calculations based on collected data.

Note. I*nvestment costs were capitalised at an annual intercalary interest rate of 2.75% up to the end of Year 3.

Table 5 presents the annual costs incurred during vineyard establishment, covering the period before the vineyard reaches full production capacity. In the analysed case, this coincides with the vineyard reaching full production capacity in the fourth year from the beginning of the investment. Based on the data presented in this table, it can be concluded that establishing a vineyard with the Prokupac grapevine variety requires substantial financial resources, with the largest shares of investment costs attributable to vineyard trellis materials, grapevine planting material, and labour.

Table 6 presents the calculation of investment costs for vineyard establishment, including capitalised interest during the establishment period (intercalary interest). Interest was calculated at an annual rate of 2.75%, corresponding to the prevailing interest rate on savings deposits. The calculation was based on the opportunity cost of capital (foregone returns), which arises when the entire investment is financed from the producer's own financial resources. Furthermore, the production value generated in Year 3 was also taken into account, as the vineyard achieved a grape yield of approximately 2 t/ha, with the corresponding production value reduced by harvesting and transportation costs. Based on these calculations, the total investment required for establishing a vineyard with the Prokupac grapevine variety was determined as the sum of investment in fixed capital (Table 6), and permanent working capital (Table 4). Accordingly, the total investment required to establish 1 ha of vineyard with the Prokupac grapevine variety amounts to 29,054.30 EUR, of which 24,929.66 EUR represents investment in fixed capital and 4,124.64 EUR represents investment in permanent working capital.

Table 7. Projected Cash Flows for Prokupac Grape Production (EUR/ha)

Year(s)	Receipts	Investment outlays	Operating & tax outlays**	Net cash flow
0	–	11,910.99	–	-11,910.99
1	–	2,227.65	–	-2,227.65
2	–	10,593.53	–	-10,593.53
3	–	4,322.14****	–	-4,322.14
4–35*	8,198.46	–	4,818.39	3,380.07
36	7,788.54	–	4,577.47	3,211.07
37	7,624.57	–	4,441.12	3,183.45
38	7,378.62	–	4,336.55	3,042.07
39	7,214.65	–	4,200.20	3,014.45
40***	11,093.33	–	4,095.63	6,997.70
Total, years 0–40	**303,450.43**	**29,054.31**	**175,839.56**	**98,556.56**

Source: Authors' calculations based on collected data.

Note: * Identical annual amounts are presented for Years 4–35 of vineyard exploitation, with all 32 years included in the total calculations.

***Operating cash outflows also include an assumed corporate income tax at a rate of 10%.*

****Receipts in Year 40 also include the full recovery of invested permanent working capital.*

***** Year 3 includes net fixed-capital investment of 197.50 EUR/ha and permanent working capital of 4,124.64 EUR/ha.*

Table 8. Dynamic Cash Flows and Net Present Value of Prokupac Vineyard Investment (7% Discount Rate; EUR/ha)

Year(s)	PV receipts	PV outlays	Present value of net cash flow	Cumulative NPV
0	–	11,910.99	-11,910.99	-11,910.99
1–3	–	14,862.87	-14,862.87	-26,773.86
4–10	36,067.20	21,197.39	14,869.81	-11,904.05
11–18	24,886.47	14,626.26	10,260.21	-1,643.84
19	2,266.94	1,332.33	934.62	-709.22
20	2,118.64	1,245.16	873.47	164.25
21–35	19,296.37	11,340.85	7,955.52	8,119.78
36–40	3,126.02	1,669.21	1,456.81	9,576.59
Total, years 0–40	**87,761.64**	**78,185.05**	**9,576.59**	**9,576.59**

Source: Authors' calculations based on collected data.

Table 9. Calculation of the Internal Rate of Return (IRR) for Prokupac Vineyard Investment (40-Year Period)

Discount rate (%)	NPV (EUR/ha)
9.50	144.90
9.60	-142.72
10.00	-1,239.52
9.55 (IRR)	–

Source: Authors' calculations based on collected data.

Table 8 shows a positive Net Present Value (NPV) of 9,576.59 EUR/ha at a discount rate of 7%. This is the higher of the two rates recommended by the Ministry of Finance of the Republic of Serbia for 2026 (5% for financial analysis and 7% for social analysis; Ministry of Finance of the Republic of Serbia, 2026) and was selected to apply more stringent investment appraisal criteria. The positive NPV indicates the economic feasibility of establishing a Prokupac vineyard under the assumed conditions. This conclusion is further supported by the Internal Rate of Return (IRR) of 9.55%, which exceeds the applied discount rate. These findings indicate that the expected return on investment exceeds the assumed cost of capital, thereby confirming the economic justification of investing in Prokupac grape production over the analysed vineyard exploitation period.

In order to provide an additional assessment of the economic feasibility of the analysed investment, the present values of cash inflows and outflows presented in Table 8 were converted into equivalent annual benefits and costs over the 40-year vineyard exploitation period. The calculation was performed using the Capital Recovery Factor (CRF), which converts present values into equivalent uniform annual amounts, according to the following formulas:

$$AE = PV \times CRF$$

$$CRF = r / [1 - (1 + r)^{-n}]$$

where AE represents the equivalent annual value, PV is the present value, r is the annual discount rate, and n is the vineyard exploitation period (years). At an applied discount rate of 7% and an investment appraisal period of 40 years, the calculated CRF amounts to 0.07500914. The results of these calculations are presented in Table 10.

Table 10. Present Values and Equivalent Annual Benefits and Costs (7% Discount Rate)

Indicator	Present value (EUR/ha)	Annualisation calculation	Equivalent annual value (EUR/ha/year)
Benefits	87,761.64	87,761.64 × 0.07500914	6,582.93
Costs	78,185.05	78,185.05 × 0.07500914	5,864.59
Net benefits (NPV)	**9,576.59**	**9,576.59 × 0.07500914**	**718.33**

Source: Authors' calculations based on collected data.

The results presented in Table 10 indicate that the present value of total benefits amounts to 87,761.64 EUR/ha, while the present value of total costs is 78,185.05 EUR/ha. By applying the Capital Recovery Factor, the equivalent annual benefits and costs were calculated at 6,582.93 EUR/ha/year and 5,864.59 EUR/ha/year, respectively. Consequently, the equivalent annual net benefit amounts to 718.33 EUR/ha/year, indicating a positive annual economic return over the analysed investment period. Furthermore, the calculated benefit–cost ratio of 1.1225 indicates that each 1 EUR of discounted costs corresponds to approximately 1.12 EUR of discounted benefits. These findings provide additional confirmation of the economic feasibility of investing in Prokupac vineyard establishment under the assumed production conditions and the applied discount rate of 7%, complementing the previously obtained NPV and IRR results.

Table 11. Dynamic Payback Period (DPP) of Prokupac Vineyard Investment

Measure	Cumulative PV (EUR/ha) / DPP	Interpretation
Year 19	-709.22	Last year with negative cumulative PV
Year 20	164.25	First year with positive cumulative PV
Dynamic payback	**19.81 years**	**Approximately 19 years and 10 months**

Source: Authors' calculations based on collected data.

Based on the results presented in Table 11, the Dynamic Payback Period (DPP) of the investment is estimated at 19 years and 10 months, representing approximately half of the total vineyard exploitation period (40 years). Considering that the total investment is recovered during the first half of the vineyard exploitation period, this indicator also confirms the economic feasibility of investing in the establishment of vineyards planted with the Prokupac grapevine variety.

Considering that the required investment expenditure and indicators of economic efficiency may vary significantly depending on production, organisational and economic factors, the results obtained in this research represent only one possible scenario. Differences in the obtained results are particularly noticeable when compared

with previous studies conducted in different geographical areas, involving different grapevine varieties and investment conditions, which reported different investment payback periods (Koprivlenski, 2016; Szabó et al., 2022; Elenov & Sredojević, 2025). Other studies dealing with similar topics have concluded that labour and mechanisation have a significant influence on total production costs, which in turn affect business performance. These studies also indicate that efficient management of production processes has a significant influence on business performance in grape production (Baptista et al., 2025; Rauhöft et al., 2026). These findings indicate the importance of considering all the specific characteristics of grape production, as well as the need to adapt investments in vineyard establishment to the actual production conditions.

Conclusions

Based on the results of the research and analyses conducted, it can be concluded that the indicators related to grape production of the autochthonous wine grapevine variety Prokupac are positive. Based on the technological and organisational production chart and the analytical cost calculation, a positive financial result of 2,727.52 EUR/ha was determined, confirming the economic profitability of grape production under the analysed conditions. In addition, the application of dynamic methods for assessing the economic feasibility of investments showed a positive Net Present Value (NPV) of 9,576.59 EUR/ha, an Internal Rate of Return (IRR) of 9.55%, and a Dynamic Payback Period (DPP) of 19.81 years, or approximately 19 years and 10 months. These indicators confirm the economic feasibility of investing in the establishment of vineyards planted with the Prokupac grapevine variety under the analysed production and economic conditions. It is particularly important to emphasise that the economic feasibility of investing in Prokupac vineyard establishment was confirmed even without government subsidies, assuming that the entire investment was financed from the producer's own funds. Based on this, it can be concluded that the economic indicators could be further improved if producers received certain subsidies. It should also be noted that the economic feasibility of investments in vineyard establishment may vary significantly. This primarily depends on achieved yields, grape selling prices, production costs, the level of mechanisation of production operations and the selected financing model. Therefore, the results of this research represent one possible scenario of the economic sustainability of Prokupac grape production, while also providing a relevant methodological basis for further organisational and economic analyses of grape production.

Accordingly, future research should focus on the development and comparative analysis of different organisational and economic models of grape production, with particular emphasis on autochthonous wine grapevine varieties. Special attention should be given to examining differences in the organisation of production processes, labour and machinery requirements, cost structures, achieved business performance and the economic feasibility of investments. In addition, the application of sensitivity analysis, scenario analysis and multi-criteria decision-making methods could contribute to

identifying the key factors influencing the economic performance of grape production, as well as developing models aimed at improving business performance in grape production. The scientific contribution of such an approach would be reflected in the systematic integration of organisational, production-technological and economic indicators, considering that comprehensive and directly comparable studies covering these aspects are still relatively limited, particularly in the viticulture sector of the Republic of Serbia. Finally, the results of this research, as well as future studies, could provide an important basis for investment decisions made by grape producers and for the development of more effective agricultural policy measures. In this context, particular attention should be paid to ensuring the long-term predictability and continuity of subsidy programmes for the establishment of new vineyards, as well as encouraging the use of new technologies that may contribute to increased productivity and reduced production costs. These measures could create more favourable conditions for the economically sustainable development of the grape production sector, improve the competitiveness of domestic producers and, in particular, support the preservation of grape production from autochthonous grapevine varieties in the Republic of Serbia.

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Conflict of interests

The authors declare no conflict of interest.

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THE ECONOMIC SIGNIFICANCE OF AGRICULTURE FOR THE DEVELOPMENT OF THE REPUBLIC OF SERBIA: TRENDS AND STRUCTURAL ANALYSIS (2016–2025)

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ABSTRACT

The subject of the research is an overview of the economic importance of agriculture in the context of the economic development of the Serbia, with a special focus on the dynamics of key economic indicators and changes in the production structure during the period 2016-2025. The aim of the research is to determine the contribution of the agricultural sector based on the analysis of GVA, intermediate consumption, factor income and the structure of agricultural production. The methodological framework is based on the application of descriptive statistical, dynamic, comparative and structural analysis. The results of the research indicates a decreasing tendency of the participation of the agriculture GVA in the GDP, alongside pronounced variability of economic indicators at the interannual level. Production structure confirmed the dominant representation of crop production, with noticeable changes in the relative importance of other production categories. The findings indicates the importance of agriculture in the economic structure of the Serbia, as well as the need to improve production efficiency, competitiveness and long-term economic sustainability.

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Introduction

The contribution of agriculture, as one of the most important economic activities, is reflected not only in the creation of GDP, but also in its connection with other sectors, employment as well as the stimulation of economic development (Gadgil & Gadgil, 2006). In this regard, as an activity that ensures the production of food and raw materials, it has multiple economic and social functions. Johnston and Mellor (1961) highlighted the importance of agriculture for economic development by emphasizing the significance of the cause-and-effect relationships between agricultural and industrial development. Seen from this perspective, agriculture contributes to economic growth through food production, providing raw materials for industrial development, generating employment and export revenues. (Alston, & Pardey, 2014; Timmer, 1992). Analogus conclusion was reached by (Byerlee & Sadoulet, 2009) emphasizing agriculture as an important initiator of structural transformation and development of closely related non-agricultural sectors. Similary, stable and productive agricultural production reduces import dependence and thus mitigates the degree of economy exposure to negative trends on the global market. Also, the growth of production along with the growth of competitiveness affects on the strengthening of the export potential and the growth of the trade balance. The importance of agriculture can be viewed from the perspective of its contribution to total employment, especially in rural areas. In this regard, the economic function of agriculture refers not only to employment in primary production but also in activities such as processing, storage, transportation and distribution of agricultural products (Pan et al., 2024; Andreeski et al., 2026). These activities creates additional value, employment, strengthen production and market connections (Kołodziejczak, 2020, Tleubayev et al., 2024). Diao et al. (2010) point out that agricultural development in the broadest sense is a trigger for economic changes, primarily through productivity growth and poverty reduction. The connection between the growth of agricultural production and the poverty decrease was additionally indicated by Christiansen et al. (2011).

In addition to the direct effects should be emphasized the indirect effects of agricultural production through the growth in demand for industrial products and services. Namely, with its growth, agricultural production increases not only the machinery consumption but also the consumption of energy sources, mineral fuels, etc. Likewise, the increase of agricultural producers revenues also affects the increase in demand for products from other activities due to increasing purchasing power. Seen from this perspective, it is clear that the real economic contribution of agriculture must be observed broadly than the direct participation in the GDP. (Johnston & Mellor, 1961; Haggblade, et al., 1989). Contemporary business conditions at the global level additionally emphasize the need to increase the productivity of agricultural production, technological innovations, but also the for increasingly rational use of natural resources (Deininger et al., 2022). Gollin (2023) came to similar conclusions, especially emphasizing that the growth of agricultural productivity is one of the most important determinants of overall economic development. In this regard, agriculture can be considered as a significant economy development potential. That is why the need to improve agricultural production and its economic efficiency is imperative. This is the only way to achieve the goals of long-term and sustainable economic development.

Methodology

The analyses of the economic importance of agriculture for the development of the Republic of Serbia is based on the quantitative analysis of secondary data. The analysis covers the period 2016-2025, which enables an overview of development tendencies and changes in the economic performance of the agricultural sector. For these purposes were used descriptive statistical, dynamic, comparative and structural analysis. The economic importance of agriculture is seen through the participation of the agriculture GVA in the GDP and its changes in annual growth rates. The analyse of economic results were based on the movement of intermediate consumption and factor income. The structure of agriculture production was examined through the ratio of crop and livestock production and the the relative share of individual categories.

A dynamic analysis was conducted to determine the direction and intensity of changes in the observed indicators, while comparisons were made at the annual level through comparative analysis. The structural analysis established the relative participation of individual categories in the total value of agricultural production. Annual changes are expressed by growth rates, and the representation of individual categories by percentage share. By applying the mentioned methods were analyzed the changes in the economic importance of agriculture, the dynamics of its economic results and the production structure, which enabled the assessment of the role of agriculture in overall economic development of the Republic of Serbia.

Agricultural gross value added (GVA) and its contribution to GDP in Serbia

The agriculture gross value added (GVA) is one of the key indicators of the economic significance of this sector. It reflects the newly created value of agricultural production reduced by the value of intermediate consumption. The analysis of GVA trends indicates a change in the volume and efficiency of agricultural production, while the participation of agricultural GVA in GDP indicates its relative importance in the economic structure (Tomšík et al., 2015). Regardless the long-term trend of a declining contribution of agriculture to overall economic activity, agriculture nevertheless still has a traditional place in the generation of national income. Užar & Radojević (2019) indicate the importance of agriculture in the formation of the total GVA, and particularly highlight the contribution of crop and livestock production. On the other hand, Novaković et al. (2024), analyzing the structure of agricultural production in Serbia, confirms the importance of individual production branches in the creation of GVA, whereby crop and especially grain production are singled out as the most significant factors. The movement of this indicator, however, is characterized by pronounced interannual oscillations, which are associated with changes in the volume of production, yields, weather and climate conditions, as well as changes in the prices of agricultural products and inputs. The following table presents data related to the share of agricultural GVA in GDP, as well as the growth rates of agricultural GVA.

Table 1. Growth rates and share of agriculture GVA in GDP (2016-2025)

Year	Share of agricultural GVA in GDP	Agriculture GVA growth rates	Year	Share of agricultural GVA in GDP	Agriculture GVA growth rates
2016	5,8	8,3	**2021**	5,3	-6,2
2017	5,1	-10,5	**2022**	5,4	-8,8
2018	5,2	21,9	**2023**	4,0	8,1
2019	5,4	-2,4	**2024**	3,3	-8,2
2020	5,2	2,4	**2025**	3,7	-0,2

Source: Author's calculations based on SORS reports

Analysis of the share of agriculture GVA in the GDP of the Republic of Serbia indicates a decline in the relative agriculture contribution to the overall economic activity. At the beginning of the observed period, the share of agriculture GVA in GDP was 5.8%, while it decreased to 5.1% in 2017. In the following years this indicator had relatively stable movement, since it ranged between 5.2% and 5.4% until 2022. However, since 2023, there has been a significant decline in share of agricultural GVA in GDP, which continued into 2024, when was recorded a record-low share of 3.3%.

In 2025 was a slight recovery (share of agricultural GVA in GDP reached to 3.7%), which, however, was not enough to reach the level from the beginning of the observed period. Taken as a whole, the share of agriculture's GVA decreased by 2.1% between 2016 and 2025, which indicates a weakening of its relative contribution to the creation of the total GDP of the Republic of Serbia. At the same time, the movement of annual growth rates of agriculture's GVA is characterized by pronounced oscillations, which indicates the uneven dynamics of the creation of added value in this sector. For example, in 2016, was positive growth rate of 8.3%, while in 2017 was recorded a decline of 10.5%. In 2018, however was a marked increase in the agriculture's GVA growth rate (21.9%), which represents the highest growth rate in the observed period. The positive trends in the agriculture GVA growth rate were already stopped in the following year, since there was a drop in the growth rate of 2.4%, while 2020 ended with a positive growth of 2.4%. In the next two years (2021 and 2022), negative dynamics was continued (agriculture GVA growth rates decreased by 6.2% and 8.8%, respectively). Although a slightly recovery in 2023, with a growth of 8.1%, the following year canceled that recovery with a drop of 8.2%. In 2025, the negative growth rate amounted only 0.2%, which indicates almost unchanged value of GVA compared to the previous year.

The movement of both indicators indicates that contribution of agriculture to the economic development of Serbia is facing two characteristic processes: the reduction of its relative participation in the GDP and pronounced oscillations in the annual GVA growth rates. It is particularly significant that the decrease in the share of agriculture GVA in GDP intensified in the latter part of the observed period, despite occasional positive GVA growth rates. This indicates the possibility that the overall economic activity, i.e. the creation of added value in other sectors, grew faster than agriculture. Taken as a whole, the results indicate a weakening of the relative economic importance

of agriculture, which further emphasizes the need to improve the productivity, investments and competitiveness of this sector, as important assumptions for its greater contribution to the long-term economic development of the Republic of Serbia.

Dynamics of intermediate consumption and factor income in Serbian agriculture (2016–2025)

The dynamics of intermediate consumption and factor income are significant indicator s of the economic performance of agriculture since it enables an overview of the production cost structure. Intermediate consumption includes the value of goods and services expended in the process of agricultural production including seeds, mineral fertilizers, plant protection products, energy, animal feed and other inputs. Its movement directly affects the level of GVA and is calculated as the difference between the value of production and intermediate consumption. Factor income is an indicator of available income for compensation of production factors (labor, land and capital). Joksimović et al. (2018) particularly indicates the importance of investment financing for economic results of the agricultural sector, while Novaković et al. (2024) highlighted the influence of the structure and intensity of production on the added value. Seen as a whole, the relationship between intermediate consumption and factor income enables the assessment of production resource utilization efficiency and the capacity of agriculture to generate income. It is particularly important to determine whether the increase in the value of production follows a proportional increase in input costs or whether is achieved a more favorable relationship between consumed resources and generated income, which indicates changes in economic efficiency and sustainability of agricultural production. The following table presents data related to the growth rates of intermediate consumption and factor income in the period 2016-2025.

Table 2. Growth rates of intermediate consumption and factor income in Serbian agriculture (2016-2025)

Year	Intermediate consumption growth rates	Factor income growth rates	Year	Intermediate consumption growth rates	Factor income growth rates
2016	8,08	11,97	**2021**	9,44	12,15
2017	-9,61	-6,22	**2022**	17,44	19,19
2018	8,91	7,81	**2023**	-4,60	-6,61
2019	3,13	0,02	**2024**	-0,5	-7,11
2020	5,93	8,64	**2025**	3,14	27,87

Source: Author's calculations based on SORS reports

Analysis of annual growth rates of intermediate consumption and factor income in agriculture in the Republic of Serbia indicates pronounced dynamics. In the observed ten-year period, phases of growth and decline alternated, with variable intensity and direction of changes on an annual basis. The observed oscillations indicates the instability movement of production costs and agricultural generated income. Intermediate consumption recorded predominantly positive growth rates in the first

half of the observed period, with the exception of 2017, when was recorded a decrease of 9.61%. In the following two years were positive growth rates of 8.91% (2018) and 3.13% (2019). This positive trend continued during 2020 and 2021, with growth rates of 5.93% and 9.44%, respectively. A particularly significant growth was achieved in 2022, when intermediate consumption recorded a growth of 17.44%. This is also the highest growth rate in the observed period. However, in the next two years there was a change in dynamics, so in 2023 was realized a decrease of 4.60%, as well as a slight decrease in 2024 of 0.50%. In 2025, positive dynamics were re-established, with an intermediate consumption growth rate of 3.14%.

The movement of factor income was characterized by even more pronounced annual oscillations. After a growth of 11.97% in 2016, in the following year was recorded a decline of 6.22%. Positive dynamics were reestablished in 2018, when factor income increased by 7.81%. The minimum growth rate of 3.14% was recorded in 2024.In 2019 (0.02%).The next three years were characterized by accelerated growth rates, especially during 2021 and 2022, when they reached 12.15% and 19.19% respectively. This was followed by a three-year period characterized by more unfavorable trends, i.e. a decrease in factor income by 6.61% in 2023 and 7.11% in 2024. In contrast, the 2025 was marked with growth of 27.87%, which represents the highest growth rate of factor income in the observed period.

From a comparative point of view, the movement of intermediate consumption and factor income shows a significant degree of coincidence in terms of the direction of changes, especially in years of more pronounced oscillations. The simultaneous decline of both categories was registered in 2017, 2023 and 2024, while their growth was particularly pronounced in 2022. However, the intensity of the changes was not uniform. While in 2022 the growth rate of intermediate consumption was 17.44%, and factor income was 19.19%, in 2025 the difference was much more pronounced, given that factor income grew at a rate of 27.87%, compared to 3.14% for intermediate consumption. This difference indicates a more favorable dynamics of factor income in relation to intermediate consumption in the last year of observation.

Based on the presented indicators, it can be concluded that intermediate consumption and factor income in the agriculture of the Republic of Serbia were characterized by pronounced oscillations, with significant differences in the intensity of annual changes. Of special importance is the trend in 2023 and 2024, when both categories recorded negative growth rates, as well as 2025, which is marked by increase in factor income. Such trends confirms the importance of simultaneously looking at the cost and income components of agricultural production, since their dynamics provide a basis for a more complete understanding of the economic performance of agriculture and its contribution to the economic trends in the Republic of Serbia.

Volume and structure of agricultural production in Serbia (2016–2025)

The volume and structure of the production of agricultural goods represent significant development indicators and agriculture production potential. Total agricultural production includes crop and livestock production, while their mutual relationship determines the production structure and affects the agriculture economic efficiency. According to Fuglie et al. (2024), changes in the volume and structure of agricultural production are associated with productivity growth, technological progress and efficiency in the use of production resources. Chavas et al. (2010), also point out that the analysis of the production structure enables a better understanding of the efficiency of resource use and market conditions adaptation.

In the Republic of Serbia, it is particularly important to analyze the ratio of crop and livestock production, as well as the participation of individual groups of products in the total value of production, since their changes affect the amount of GVA, factor income and agriculture market competitiveness. The following table presents data related to the value of production of agricultural goods in millions of RSD, as well as the share of crop and livestock production in the period 2016-2025.

Table 3. The value of agricultural production and the share of crop and livestock production (in millions of RSD)

Year	Production of agricultural goods	Crop %	Livestock %	Year	Production of agricultural goods	Crop %	Livestock %
2016	574 817,9	72,96	29,04	**2021**	707 213,2	76,95	23,05
2017	529 890,4	67,38	32,62	**2022**	821 507,6	71,93	28,07
2018	574 703,9	69,34	30,66	**2023**	752 671,7	69,26	30,74
2019	589 978,3	70,26	29,74	**2024**	712 127,8	67,03	32,97
2020	632 360,9	71,86	28,14	**2025**	776 728,7	68,99	31,01

Source: Author's calculations based on SORS reports

Trends in the total value of production of agricultural goods in the Republic of Serbia in the period 2016–2025. indicates long-term growth. In 2016, the value of production was RSD 574,817.9 million, while in the following year there was a drop of RSD 44,927.5 million. After that, there is a noticeable tendency of growth, with a maximum of RSD 821,507.6 million reached in 2022. In the following two years was recorded a decline, with the value falling to RSD 752,671.7 million (in 2023), and RSD 712,127.8 million (in 2024), while 2025 was the year of revitalization, since the value of production was at the level of RSD 776,728.7 million. Compared to the initial year of observation, the nominal value of production in 2025 was higher by 35.1%. Structural analysis shows that crop production has a dominant role in the formation of the total value of agricultural goods. This claim is based on the fact that its participation ranged from 67.03% in 2024 to a maximum of 76.95% in 2021. In 2016, crop production accounted for 72.96% of the total value, while in 2017, its share decreased to 67.38%. In the following years were recorded oscillations, with the highest share in 2021. This was

followed by a decline in its relative importance, particularly pronounced in 2024, while in 2025 the share increased to 68.99%. On the other hand, livestock production had not only a smaller share in the total value of agricultural goods, but also more significant oscillations. In 2016, livestock production accounted for 29.04% of total agricultural production, while in 2017 its share increased to 32.62%. This was followed by a decline with minimum share of 23.05% reached in 2021. In the following years, the relative importance of livestock production grew again, with a maximum share of 32.97% achieved in 2024.

Comparative analysis confirms the dominant position of crop production, but also the variability of the relationship between the two basic components of agricultural production. The biggest difference in their participation was recorded in 2021, when crop production accounted for 76.95% and livestock production for 23.05%. On the other hand, 2024 was characterized by the smallest share of crop production (67.03%) and the largest share of livestock production (32.97%). Such trends indicates changes in the relative contribution of these two production branches to the total value of agricultural goods.

Seen as a whole, the results of the analysis indicate an increase in the nominal value of agricultural production in the Republic of Serbia, while maintaining the dominant position of crop production. At the same time, oscillations in the structural participation of crop and livestock production indicates the volatility of the production structure of the agricultural sector. Improving the productivity, technological equipment and competitiveness of both production branches is a significant prerequisite for strengthening the production potential of agriculture and increasing its contribution to the overall economic development of the Republic of Serbia.

Dynamics and structure of crop production in Serbia (2016–2025)

The dynamics and structure of crop production provides insight into changes of the volume of production, representation of certain crops and their contribution to the total value of agricultural production. The volume and structure of crop production depends on numerous factors: natural conditions, available land resources, applied technology, productivity and market trends. Grujić et al. (2020), point out to significant differences in the representation of certain crops and their yields. Dimovski, et al. (2023) emphasize the importance of structural changes in agricultural production in understanding production potential and food security. Novaković et al. (2024) confirms the dominant contribution of crop production, especially cereals, to the formation of the agriculture GVA. Therefore, the analysis of the dynamics and structure of crop production enables the assessment of changes in the production orientation, the efficiency of the agricultural resources and the contribution of individual production branches to the overall economic results. The following table presents data related to the growth rates of the value of crop production in the period 2016-2025.

Table 4. Dynamics and structure of crop production in Serbia (2016–2025)

Year	2016	2017	2018	2019	2020
Growth rate of crop production value	19,17	-14,86	11,61	4,02	9,62
Share of cereal value in crop production	39,31	31,86	39,4	38,27	37,56
Share of industrial and fodder crops value in crop production	20,51	22,25	22,88	23,33	23,25
Share of fruit value in crop production	17,88	21,56	17,27	16,18	19,75
Share of vegetable value in crop production	12,99	12,39	9,87	10,46	9,05
Year	**2021**	**2022**	**2023**	**2024**	**2025**
Growth rate of crop production value	19,76	8,58	-11,79	-8,43	12,27
Share of cereal value in crop production	39.88	38,19	36,05	31,26	30,91
Share of industrial and fodder crops value in crop production	21,19	19,19	21,98	19,55	18,28
Share of fruit value in crop production	20,25	21,70	14,37	19,66	23,80
Share of vegetable value in crop production	9,15	10,32	12,71	16,90	14,91

Source: Author's calculations based on SORS reports

Crop production growth rates in the Republic of Serbia were characterized by significant interannual oscillations. It is worth noting that the highest growth rate was recorded in 2021 (19.76%), whereas the sharpest decline occurred in 2017 (-14.86%). However, positive growth rates were recorded in almost all years during the first half of the observed period, with the exception of 2017. In the second half of the period, negative growth rates were recorded in 2023 and 2024, amounting to 11.79% and 8.43%, respectively. In 2025, a growth rate of 12.27% was recorded, indicating a recovery following two consecutive years of negative growth.

The structural analysis of crop production indicates the dominance of cereals, whose share ranged from 30.91% to 39.88%. Following the peak recorded in 2021, their share declined almost continuously in the subsequent years. Industrial and fodder crops represented the second-largest category, accounting for between 18.28% and 23.33% of total crop production. Their share remained relatively stable until 2021, after which more pronounced fluctuations and a downward trend were observed, particularly in the final two years of the period under review.

The share of fruit in crop production exhibited considerable fluctuations, ranging from 14.37% to 23.80%. Particular emphasis should be placed on the increase in its share during the final three years of the observed period, reaching a peak in 2025. Vegetable production accounted for the smallest share among the analyzed categories; however, its relative importance within the crop production structure showed an increasing trend. After declining from 12.99% in 2016 to 9.05% in 2020, the share of vegetables increased, reaching a peak of 16.90% in 2024.

From a comparative point of view, the structure of crop production is characterised by the dominant participation of cereals, significant participation of industrial and fodder crops and slightly less fruits and vegetables. Nevertheless, the decrease in the relative representation of cereals and the increase in the share of fruits and vegetables in certain

years indicate changes in the structure of crop production. Such developments point to the importance of production diversification. Overall, crop production in the Republic of Serbia in the analyzed period was characterized by unstable dynamics and changes in the structural representation of certain groups of products. Although cereals have retained their leading position, changes in the participation of other categories indicate the need for continuous improvement of the production structure. Increasing productivity, technological modernization and competitiveness of various branches of crop production is an important prerequisite for strengthening the economic potential of agriculture and its contribution to the overall economic development of the Republic of Serbia.

Dynamics and structure of livestock production in Serbia (2016–2025)

The dynamics and structure of livestock production represent significant indicator of the development of the agricultural sector and its ability to respond the domestic and international market requirements. Livestock production includes the cattle farminng, pigs, sheep, goats and poultry, as well as the production of meat, milk, eggs and other animal origin products. Its movement depends on the livestock size and structure, productivity, production costs, technological equipment and market conditions. Arsić et al. (2012) indicates the connection between changes in livestock and the volume of meat production in the Republic of Serbia, while Čekić et al. (2007) emphasize the importance of improving sheep and goat production. Stevanović et al. (2018) emphasize the importance of market meat production for the assessment of agricultural development. Milićević et al. (2025) point out to the long-term structural and economic challenges of livestock farming in Serbia, especially in terms of the number of heads, productivity and competitiveness. Therefore, the analysis of the dynamics and structure of livestock production enables an overview of changes in the representation of individual production branches, their contribution to the total value of agricultural production and the possibility of improving the economic efficiency of this sector. The following table presents data related to the growth rate of livestock production value and the growth rate of the value of livestock product output in the period 2016-2025.

Table 5. Dynamics and structure of livestock production in Serbia (2016–2025)

	2016	**2017**	**2018**	**2019**	**2020**
Growth rate of livestock production value	-8,06	11,21	1,94	-0,42	1,42
Share of livestock value in livestock production	67,10	69,71	65,00	69,52	69,64
Growth rate of the value of livestock product output	-11,87	2,39	17,77	13,27	1,03
Share of the value of livestock product output	32,90	30,29	35,00	30,48	30,36
	2021	**2022**	**2023**	**2024**	**2025**
Growth rate of livestock production value	-8,39	41,45	0,35	1,46	2,57
Share of livestock value in livestock production	68,60	69,01	71,25	68,15	68,56
Growth rate of the value of livestock product output	-5,27	39,65	-6,91	12,39	1,25
Share of the value of livestock product output	31,40	30,99	28,75	31,85	31,44

Source: Author's calculations based on SORS reports

Analysis of the growth rate of livestock production value in the Republic of Serbia indicates pronounced interannual oscillations. In 2016 was recorded a decrease of 8.06%, compared to 2017 and the growth of 11.21%. In the following period, the dynamics were more moderate, with a slight decrease of 0.42% in 2019 and a negative movement of 8.39% in 2021. The 2022 stands out in particular, recording a pronounced growth rate of 41.45%, while the period from 2023 to 2025 was characterized by more stable dynamics, with positive but relatively modest growth rates.

Structural analysis shows that livestock production represents the dominant component of total livestock production. Its participation ranged from 65% in 2018 to 71.25% in 2023, while during most of the observed period it remained at a level of approximately 68–70%. After the increase in 2023, the participation was reduced to 68.15% in 2024, and reached 68.56% in 2025. These indicators confirms the continued dominance of livestock production.

Value of livestock product output had a smaller share, ranging from 28.75% in 2023 to 35.00% in 2018, with more pronounced oscillations in growth rates. After a drop of 11.87% in 2016, in the following three years were achieved positive growth rates, especially in 2018 and 2019, when they amounted to 17.77% and 13.27%. In 2021 was recorded a decrease of 5.27%, compared to 2022 and an increase of 39.65%. After another decrease in 2023 (6.91%), a growth of 12.39% followed in 2024, while in 2025 the growth rate slowed down to 1.25%.

Comparative analysis indicates a relatively stable structure of livestock production, in which share of livestock value in livestock production was bigger than share of the value of livestock product output. However, differences in growth rates point to different dynamics of individual components. The 2022 stands out in particular, as both categories recorded high growth rates, whereas 2023 was characterized by divergent trends, with a slight increase in livestock production and a decline in the production of livestock products. In 2024, the opposite pattern was observed, with more pronounced growth in the latter category.

Overall, livestock production in the Republic of Serbia is characterized by variable value dynamics and a relatively stable structural representation of basic components. The dominant participation of livestock production confirms its importance in the formation of the total value of this segment of agriculture, while oscillations in the production of livestock products indicates room for improving productivity and efficiency. Modernization of production capacities, improvement of livestock quality and development of processing capacities are important prerequisites for strengthening the competitiveness of livestock production and increasing its contribution to the economic development of the Republic of Serbia.

Conclusion

The research results indicates that agriculture represents a significant component of the economy of the Republic of Serbia. Nevertheless, the economic contribution is characterized by significant fluctuations in basic economic indicators and gradual changes in the production structure. It should be borne in mind that the importance of agriculture cannot be seen solely on the basis of its participation in the GDP, but also through the movement of GVA, intermediate consumption, factor income and the structure of agricultural production.

The movement of the agriculture GVA indicates the instability of economic performance since the share in the GDP decreased from 5.8% to 3.7% during the observed period. At the same time, the change of interannual GVA rates indicate alternating periods of growth and decline, which confirms the pronounced variability of the economic contribution of agricultural activity. The aforementioned developments point to a relative decrease in the participation of agriculture in the creation of the total GVA of the national economy, but still do not significantly reduce its strategic importance in the economic structure of the Republic of Serbia.

During the observed period were established a significant interannual oscillations through the analysis of intermediate consumption and factor income. In some years, their movements were coordinated, while in others were noted differences in the intensity of changes. The year 2025 stands out in particular, as factor income recorded a growth rate of 27.87%, compared with a 3.14% increase in intermediate consumption. This indicates changes in the economic results of agricultural production, but also the need for their continuous monitoring in order to assess economic conditions and the income position of the agricultural sector.

The structural analysis of agricultural production confirms the dominant representation of crop production. Its share ranged from 67.03% to 76.95%, while livestock production accounted for a relatively smaller, yet stable, proportion. In crop production, a decline in the relative share of cereals and an increase in the share of fruit were observed in the final years. Livestock production participation was generally around 66% of the total value of livestock production, while livestock products made up the remaining part.

Based on the analysis, it can be concluded that the economic importance of agriculture in the Republic of Serbia is manifested through its contribution to the creation of the GDP, the realization of factor income and the provision of diverse agricultural production. At the same time, the observed instability of economic indicators and changes in the production structure indicates the need to improve production efficiency, strengthen competitiveness and create more favorable conditions for more stable development of the agricultural sector. In this context, the long-term improvement of its contribution to the overall economic development requires a systemic approach that implies more efficient use of production resources, improvement of the production structure and strengthening of the economic sustainability of agricultural activities.

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Conflict of interests

The authors declare no conflict of interest.

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DEMOGRAPHIC CHANGE, LAND USE AND LIVESTOCK DYNAMICS: TRADITIONAL FOOD PRODUCTS AS A CHANCE FOR RURAL DEVELOPMENT IN THE MUNICIPALITY OF PIROT

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ABSTRACT

Rural development in the Municipality of Pirot, Serbia, is influenced by demographic decline, land-use changes, and livestock reductions, all of which are closely tied to the production of traditional foods. Drawing on census data (1991-2022), official statistics, and field research, the study highlights a 26.7% population decline and pronounced aging, threatening agricultural sustainability. Although livestock numbers and milk production have decreased, traditional products: Pirot Kachkaval, Peglana Sausage, and Vurda retain vital economic and cultural roles. Branding and geographical indications would strengthen local competitiveness and present viable strategies for rural revitalization. CORINE Land Cover data reflect deagrarization through reduced pasture and arable land, alongside other climatic and anthropogenic influences. These combined dynamics underscore both the vulnerability and lasting potential of Pirot's rural areas. Traditional knowledge, product identity, and environmental adaptation are crucial to long-term sustainability.

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Introduction

Globally, agriculture remains a cornerstone of food security, rural livelihoods, and sustainable development, contributing to the Sustainable Development Goals related to hunger, climate, and biodiversity (FAO, 2023). In the Balkans, it sustains traditional landscapes and regional economies, while in Serbia, it supports GDP, rural employment, and cultural identity through authentic products that strengthen competitiveness (Nikolić et al., 2017). The Municipality of Pirot, located on the slopes of Stara Planina, combines rich natural resources with a strong livestock heritage 63,194 ha of the Stara Planina Nature Park's total area of 142,219 ha (Stankov et al., 2011). European and national frameworks emphasise ecological networks and biodiversity protection (Dobričić et al., 2017; Convention on Biological Diversity, 2018), while Pirot has demonstrated how protected landscapes have enhanced forage quality and the authenticity of traditional dairy products such as Pirot Kachkaval (Tomić et al., 2011). Livestock farming and indigenous breeds like Pirot Pramenka have underpinned PDO (Protected Designation of Origin)-protected products such as Pirot Kachkaval and Pirot Peglana Sausage (Ružić-Mušlić et al., 2011; Tasić et al., 2019; Grujović et al., 2024; Intellectual Property Office of the Republic of Serbia, n.d.-a; n.d.-b), supported by the Dairy School "Dr Obren Pejić", which produced 127.76 tons of cheese in 2024 (Dairy School "Dr Obren Pejić", 2025). Yet depopulation, ageing, and limited market visibility have weakened rural capacity (Marković et al., 2025; Užar, 2022).

In addition to alarming demographic trends, deagrarization has become clearly visible in the field, where many pastures have now been dominated by thorny shrubs and dense, inaccessible vegetation. Strengthening geographical branding can therefore enhance product value, cultural identity, and sustainable rural development by linking traditional practices, natural resources, and branding to regional competitiveness (Radivojević et al., 2024; Albaladejo-García et al., 2024; Babović et al., 2016). This study investigates the relationship between demographic change, land-use dynamics, and livestock farming in the Municipality of Pirot by integrating CORINE Land Cover analysis with official demographic and livestock statistics to assess implications for traditional food production and rural development. This approach links these processes at the municipal level, which has been largely overlooked in previous studies.

Materials and methods

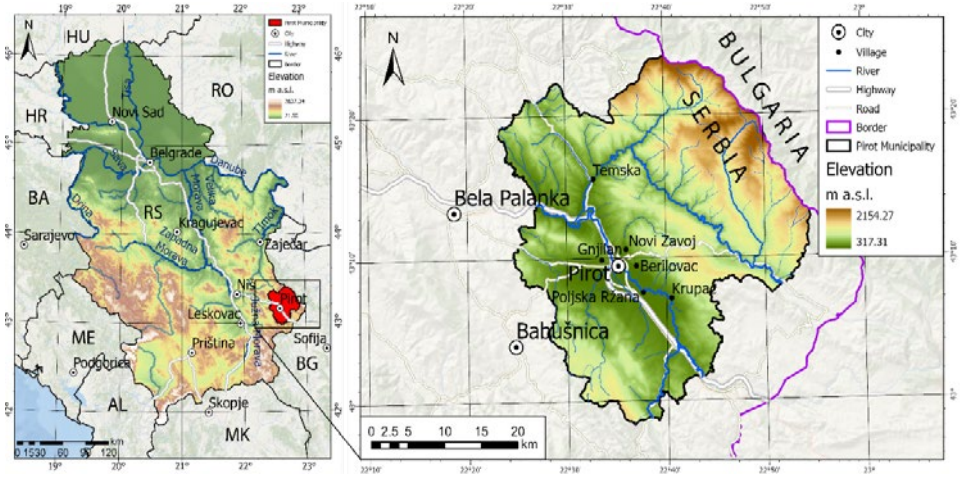
Study Area

The study area encompasses the Municipality of Pirot, located in southeastern Serbia along the Bulgarian border, covering 1,232 km² as the administrative, economic, and demographic core of the Pirot District (2,761 km²). The terrain ranges from 250 m a.s.l. in the valleys to 2,169 m a.s.l. at Midžor Peak on Stara Planina. The study area abounds in pronounced geomorphological diversity: valleys, basins, and ridges, which shape settlement and land use. The Nišava Valley, running southeast-northwest, forms the main settlement axis (Ivković & Todorić, 2013). The entire area falls within the

Carpathian-Balkan mesoregion, which is part of the Mountain-basin-valley macro-region of Serbia (Pavlović, 2019). Geological diversity provided the basis for the formation of different pedological types. There are pedological formations such as mountain soils, vertisol, smonica, and on the lower terrain, deposits of alluvial sediments. Most soils are characterised by a developed pedological structure and belong to the second and third soil quality classes. The continental climate with mountain influences creates ecological gradients that affect agriculture. Depopulation and labour shortages, coupled with rising temperatures, irregular precipitation, and summer aridity, lead to deagrarization, farmland abandonment and threaten rural sustainability (Martić Bursać et al., 2024; Manojlović et al., 2018). The Stara Planina Nature Park integrates biodiversity protection with traditional landscapes and supports ecotourism as a sustainable development model (Stankov et al., 2011; Cvetković et al., 2023).

Demographically, Pirot faces long-term population decline and ageing, driven by emigration and low fertility. This resulted in land abandonment and urban concentration (Petrović et al., 2024; Malinić et al., 2025). The municipality includes 72 rural settlements, where lowland villages such as Gnjilan, Berilovac, Krupac, and Poljska Ržana, with over 1,000 residents in 2022, exhibit relative resilience and agricultural vitality. In contrast, upland communities like Temska, Dojkinci, and Gostuša experience severe depopulation and farmland loss (Census, 1948-2022; City Population, 2022; EU PRO Plus, 2024; Marković et al., 2025). Between 1991 and 2022, Pirot's population fell from 67,658 to 49,601 (-26.7%), aligning with an average 28% decline across Serbia's border municipalities (Malinić et al., 2025). This contrast between productive lowlands and declining mountain zones encapsulates Pirot's spatial duality and illustrates the intertwined demographic, climatic, and agrarian challenges defining the region's development trajectory.

Figure 1. Geographical position of the Municipality of Pirot



Source: Authors'

Demographic, Land Use and Agricultural Data Gathering

Demographic data were obtained from the population censuses of 1948, 1953, 1961, 1971, 1981, 1991, 2002, 2011, and 2022, conducted by the Statistical Office of the Republic of Serbia. These datasets provide comprehensive information on population size, age structure, migration trends, and settlement distribution. In addition to descriptive statistics, the average age of the population was determined using the weighted mean formula:

$$\bar{x} = \frac{\sum(N_i \times M_i)}{\sum N_i}$$

where *Ni* is the number of inhabitants in each age group and *Mi* is the midpoint of the corresponding age interval (Shryock & Siegel, 1980; Siegel & Swanson, 2004). This approach enabled a precise assessment of demographic ageing across both lowland and highland areas of the municipality.

Agricultural data were drawn from national agricultural censuses (1960, 1980, 2012, 2023), statistical yearbooks, and municipal datasets documenting land use, livestock, and production structures. These sources enabled the identification of long-term trends in farmland abandonment and herd reduction. Demographic and agricultural indicators were correlated to examine the links between population decline, land-use change, and rural transformation.

Spatial patterns were analysed using ArcGIS Pro 2.5.0 and CORINE Land Cover (2006, 2012 and 2018) data, mapping settlement distribution, agricultural zones, and reforestation. Local dairy data from the Dairy School "Dr Obren Pejić" in Pirot supported the assessment of milk inflow and PDO-labelled Pirot Kachkaval, compared with traditional European cheeses to illustrate its broader significance.

The methodological framework follows EU CAP principles of sustainable rural development, indigenous breed protection, and valorisation of local products, integrating demographic, agricultural, spatial, and dairy-sector analyses to interpret rural sustainability in the Pirot region.

Results

This section presents the results of demographic, land-use, and agricultural analyses in Pirot, focusing on population trends, changes in land-use, livestock dynamics and dairy production. Special attention is given to rural depopulation, population ageing, and herd reduction, as well as their impacts on traditional products such as Pirot Kachkaval, Vurda, and Peglana Sausage.

Demographic Changes

The long-term process of depopulation in Southeastern Serbia is particularly evident in the Pirot District, where census data indicate a continuous population decline across all municipalities (Table 1).

Table 1. Population changes in the Pirot District and the Municipality of Pirot according to census data, 1991-2022 and population estimates for 2024.

	Pirot District	Pirot Municipality	Babušnica Municipality	Bela Palanka Municipality	Dimitrovgrad Municipality
1991	116,926	67,658	19,333	16,447	13,488
2002	105,654	63,791	15,734	14,381	11,748
2011	92,479	57,928	12,307	12,126	10,118
2022	76,700	49,601	9,109	9,947	8,043
2024[1]	74,951	48,709	8,699	9,703	7,840

Source: Statistical Office of the Republic of Serbia (2022). Comparative overview of the number of inhabitants 1948-2022. Available at: https://popis2022.stat.gov.rs/media/31418/4_uporedni-pregled-broja-stanovnika-1948-2022.xlsx

Table 1 shows a continuous decline in the population of the Pirot District and its four municipalities between 1991 and 2022. The most significant decrease was recorded in Babušnica, while the Municipality of Pirot experienced the lowest relative loss.

Data from the Statistical Office of the Republic of Serbia (Census, 2002; 2022) show an increase in average age in the Pirot region. The average age in the Municipality of Pirot rose from 41.8 years in 2002 to 46.4 years in 2024, and in the Pirot District from 43.5 to 47.4 years. Rural areas recorded higher average ages, reaching 50.2 years compared to 44.9 years in urban settlements. Women averaged 51 years, while men averaged approximately 47 years.

Table 2. The five largest villages in the Municipality of Pirot by population (including Novi Zavoj as the sixth), 1948-2022.

Village	***1948***	***1953***	***1961***	***1971***	***1981***	***1991***	***2002***	***2011***	***2022***
Berilovac	622	608	563	687	1,051	1,632	1,933	1,838	1,660
Gnjilan	1,342	1,353	1,341	1,453	1,474	2,143	2,478	2,520	2,199
Krupac	2,711	2,577	2,245	1,924	1,883	1,635	1,444	1,302	1,028
Novi Zavoj[2]	1,693	1,526	1,485	180	1,222	1,538	1,458	1,373	1,200
Poljska Ržana	976	959	909	946	1,114	1,306	1,349	1,276	1,181
Temska	2,244	2,224	2,029	1,736	1,435	1,162	908	719	449

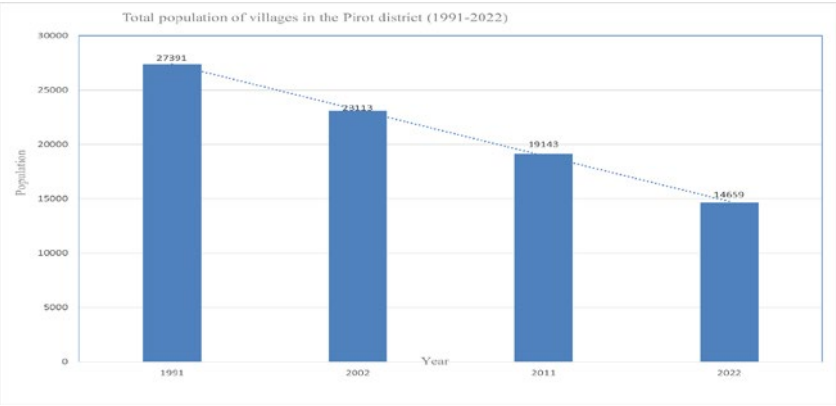
Source: Statistical Office of the Republic of Serbia (2022). Comparative overview of the number of inhabitants 1948-2022 https://popis2022.stat.gov.rs/media/31418/4_uporedni-pregled-broja-stanovnika-1948-2022.xlsx

6 Note: Data for 2024 represent estimated population figures provided by the Statistical Office of the Republic of Serbia, not census results.

7 The village of Zavoj was submerged in a catastrophic landslide in February 1963, after which all residents were relocated to a part of the city of Pirot known today as a Novi Zavoj (Marković et al., 2024). Although it no longer represents a rural settlement, it is included in the table to highlight the significance of the Zavoj disaster.

Demographic trends in the Municipality of Pirot between 1948 and 2022 show continuous population decline. According to the Statistical Office of the Republic of Serbia (2022), all major villages recorded population decline after 1991, with only minor increases observed in lowland areas near Pirot city. Gnjilan remained the largest settlement, increasing from 1,342 inhabitants in 1948 to 2,520 in 2011, before declining to 2,199 in 2022. Krupac decreased from 2,711 to 1,028 inhabitants, while Poljska Ržana increased from 976 to 1,181. In contrast, mountain villages such as Temska and Zavoj experienced substantial population losses. Temska declined from 2,244 to 449 inhabitants, representing a reduction of approximately 80% (Table 2; Marković et al., 2025).

Figure 2. Total rural population of the Municipality of Pirot, 1991-2022.



Source: Statistical Office of the Republic of Serbia (2022). Comparative overview of the number of inhabitants 1948-2022. Retrieved from https://popis2022.stat.gov.rs/media/31418/4_uporedni-pregled-broja-stanovnika-1948-2022.xlsx, Author's calculation based on census data.

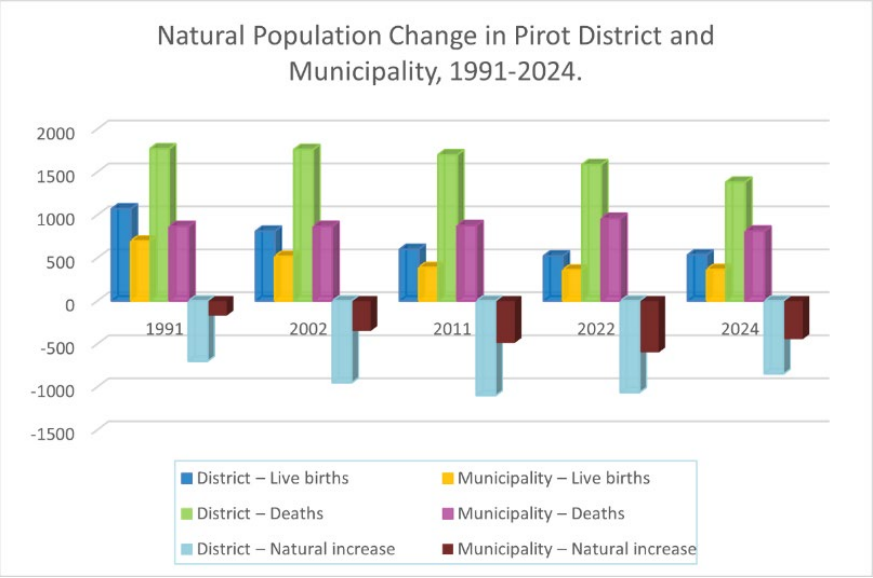
Figure 2 presents the total rural population of the Municipality of Pirot based on census data from 1991 to 2022. Over this period, the rural population decreased by almost half.

According to data from the Statistical Office of the Republic of Serbia (Census, 2022), population numbers in both the Pirot District and the Municipality of Pirot declined between 1991 and 2024. The population of the Pirot District decreased from 116,926 in 1991 to 74,951 in 2024, while the population of the Municipality of Pirot decreased from 67,658 to 48,709.

Natural population decrease in the Pirot district ranged from -699 in 1991 to -847 in 2024. In the Municipality of Pirot, the natural population ranged from -170 in 1991 to -445 in 2024.

The number of live births declined from 1,073 in 1991 to 536 in 2024 in the Pirot district and from 698 in 1991 to 368 in 2024 in the Municipality of Pirot. Throughout the observed period, the number of deaths exceeded the number of live births. (SORS, *Natural Change of Population*, 2022).

Figure 3. Natural population change in the Pirot District and Municipality of Pirot, 1991-2024.



Source: Statistical Office of the Republic of Serbia, Natural Change of Population, 1991-2024 (census data and population estimates).

Figure 3 presents natural population change in the Pirot District and the Municipality of Pirot, for the period 1991-2024.

Table 3. Population by place of birth and migration origin in Pirot District and the Municipality of Pirot, 2022.

Area	Total population	Lives in the same settlement since birth	Total migrants (all)	Total migrants from Serbia	Migrants from the former SFRY republics	Migrants from other countries	Migrants from an unknown country of migration
Pirot District	76,700	43,055	33,645	30,628	1,357	1,653	7
Municipality of Pirot	49,601	29,000	20,601	18,616	903	1,078	4

Source: Statistical Office of the Republic of Serbia, 2022 Census of Population, Households and Dwellings. https://publikacije.stat.gov.rs/G2023/Html/G20231189.html

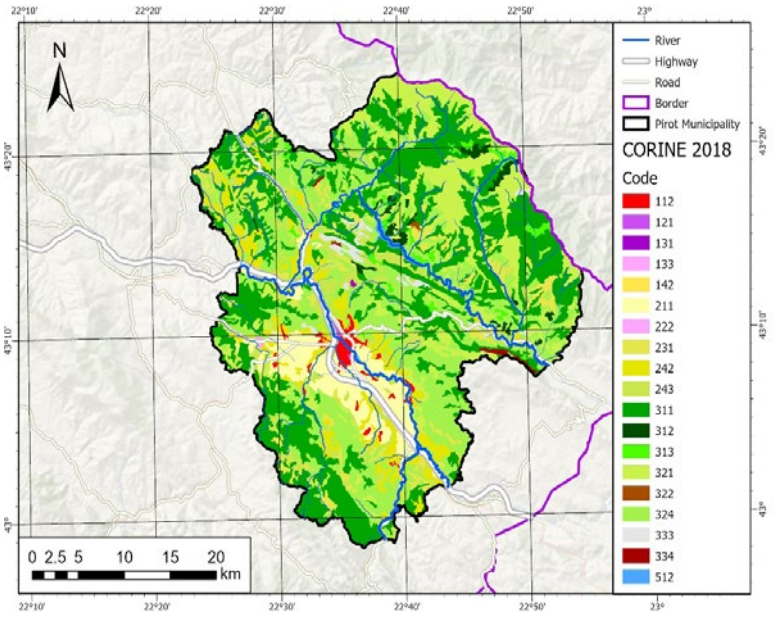
Table 3 shows that the majority of the population in both the Pirot District and the Municipality of Pirot has lived in the same settlement since birth. Most migrants originate from Serbia, while a smaller share originates from the former SFRY republics and other countries.

Land use change based on CORINE data and the number of livestock changes

Land use and livestock patterns in the Pirot District and the Municipality of Pirot have changed in recent decades. Agricultural land, including arable fields and pastures, shows a decline, while livestock numbers have decreased across all major categories, largely associated with depopulation, rural abandonment, and structural changes in the local economy. In particular, livestock numbers declined sharply in sheep and cattle herds.

The following tables present the key trends in land use categories and livestock numbers, showing the direction and magnitude of these changes. To provide a spatial perspective, CORINE Land Cover (2018) data were analysed for the Municipality of Pirot. These data show the distribution of forests, arable land, and pastures across lowland and upland zones, enabling visualization of how demographic decline and agricultural contraction have reshaped the local landscape.

Figure 4. Land use of the Municipality of Pirot based on CORINE Land Cover (CLC) data, 2018.



Source: Authors' elaboration based on CORINE Land Cover data (EEA, 2018).

CORINE Land Cover (2018) shows the spatial distribution of land use categories in the Municipality of Pirot (Figure 4). Forest areas are predominantly located in the mountainous parts of Stara Planina, while arable land and pastures are mainly concentrated in the Nišava Valley and in the vicinity of the town of Pirot. Differences in land-use composition are observed between lowland and upland settlements.

Table 4. Land cover changes in the Municipality of Pirot, 2006, 2012 and 2018 (ha)

Land cover class	2006 (ha)	2012 (ha)	2018 (ha)	Change 2006-2018 (ha)
112 Urban areas	1,348.2	1,499	1,522.9	174.7
211 Arable land	8,262.7	8,237.3	8,237.3	-25.4
231 Pastures	8,870.2	8,584.6	8,579.4	-290.8
242 Complex cultivation	8,440.6	8,747.5	8,693.1	252.5
311 Broad-leaved forest	39,528.8	39,333	39,255.9	-273
312 Coniferous forest	1,297.9	1,423.8	1,423.8	125.9
313 Mixed forest	1,646.3	1,733.3	1,733.3	87
321 Natural grasslands	15,731.9	16,008.3	16,003.1	271.2
324 Transitional woodland–shrub	31,642.6	31,021.0	31,029.3	-613.3
334 Burnt areas	0	231.6	295.9	295.9

Source: Authors' calculation based on CORINE Land Cover (EEA, 2018).

Table 4 shows that between 2006 and 2018, urban areas in the Municipality of Pirot increased slightly (+174.7 ha), while arable land (-25.4 ha) and pastures (-290.8 ha) declined. Complex cultivation mosaics expanded (+252.5 ha), whereas broad-leaved forests decreased (-273.0 ha). Natural grasslands expanded for 271.2 ha, while burnt areas also increased by 295.9 ha. The largest decrease was observed in Transitional woodland–shrub, which fell by 613.3 ha.

In 1955, sheep numbers in the Pirot District exceeded 270,000 head (the exact number is 272,309), while the number in 1960 was 268,865 head (Belić et al., 1960; Stevanović et al., 2016a). During the same period, cattle herds numbered 32,062 in 1937 and 41,662 head in 1960. Horse numbers decreased from 7,578 head in 1937 to 6,359 head in 1960. Pig production fluctuated over time, reaching 16,031 head in 1937 and 20,842 head in 1958. Poultry numbers amounted to 172,620 heads in 1937 and 209,539 heads in 1960.

According to official data from 2023, the total number of sheep in the Municipality of Pirot amounted to 11,216 heads. Horse numbers totalled 156 head. In addition, the livestock structure included 4,009 head of cattle, 7,798 pigs, and 46,303 poultry. Similar declining trends were recorded across other livestock categories. Beekeeping was the only agricultural sector that exhibited stagnation during the observed period (Radivojević et al., 2024).

Milk intake and dairy production in the Municipality of Pirot were analysed for the period 2019-2024. Average daily cow's milk intake decreased from 4,651.71 l in 2019 to 4,228.72 l in 2024. The largest monthly decreases were recorded in January (-15%) and May (-14%), with a total 2024/2023 production index of 94.56.

Between 2021 and 2024, cow's milk production decreased by 3.6%, while goat's milk production decreased by 21.8% and sheep's milk production decreased by 38.1%. Changes were also recorded in the structure of dairy products. Fresh cheese production

increased by more than 35%, while yoghurt and pasteurized milk decreased by 6-9%. Kachkaval and Pirot Kachkaval decreased by -4 to -7%. Organic dairy products decreased by more than 60%.

Discussion

Demography

Demographic trends in the Municipality of Pirot indicate a long-term and spatially differentiated process of depopulation, particularly pronounced in rural areas. Between 1991 and 2022, the Pirot District lost more than one third of its population, while the Municipality of Pirot recorded a decline of 26.7% (Census, 2002, 2011, 2022). During the same period, the average age increased from 39 to 46.4 years, reflecting strong population ageing driven by low fertility rates and sustained out-migration of younger cohorts (Jelić et al., 2019).

Despite this overall negative trend, clear contrasts exist between lowland and highland settlements. Lowland villages such as Gnjilan, Krupac, and Poljska Ržana have remained relatively resilient due to fertile soils, favorable agricultural conditions, and good accessibility within the Nišava Valley (Cartwright & Drobnjaković, 2021; EU PRO Plus, 2024). Gnjilan recorded 2,478 inhabitants in 2002, 2,520 in 2011, and 2,199 in 2022, while Poljska Ržana declined from 1,349 in 2002 to 1,181 in 2022 (Census, 2002, 2011, 2022; City Population, 2022). In contrast, highland settlements have experienced severe population losses. Temska declined from 3,745 inhabitants in 1931 to 908 in 2002 and fewer than 450 in 2022, illustrating a long-term depopulation trajectory (Cartwright & Drobnjaković, 2021; Leščešen et al., 2013; Stojsavljević et al., 2015; EU PRO Plus, 2024).

The Visok microregion, predominantly located within the Municipality of Pirot, represents an extreme case of rural depopulation. Across its 22 villages, the population decreased from 14,706 in 1948 to only 504 inhabitants in 2022, with an average age of 66.44 years, indicating an advanced stage of demographic collapse driven by long-term out-migration, ageing in place, and the decline of local economic functions (Marković et al., 2024; 2025).

These strong spatial disparities are also reflected in land-use patterns. CORINE Land Cover data show that arable land, dominant in lowland areas, declined by only 25.4 ha, while pasture areas, characteristic of highland zones, decreased by as much as 290.8 ha. This correspondence between demographic decline and land-use change confirms asymmetric rural development and highlights the need for territorially differentiated, place-based approaches that integrate demographic and land-use policies to support sustainable development across the entire region (Statistical Office of the Republic of Serbia, 2022).

Land Use Changes

Land use in the Municipality of Pirot closely reflects long-term demographic decline, but also major changes due to forest fires. Census and CORINE Land Cover data indicate that farmland abandonment follows rural depopulation, particularly in the villages of Stara Planina. Between 2006 and 2018, pasture areas decreased by nearly 300 ha, while arable land declined by approximately 25 ha in the Municipality of Pirot (Malinić et al., 2025). It is clearly visible in Table 4 that shrublands decreased the most. This result was obtained due to the vast mountain fire in 2007, when about 2,500 ha of the total area was caught by fire (Živanović & Gocić, 2023). Due to ongoing forestry activities, forest fires and complex climatic changes, the structure of forest cover is gradually changing, with a declining share of deciduous forests.

Traditionally based on sheep farming and the floristic diversity of Stara Planina pastures, the rural economy has weakened as a result of declining livestock numbers, particularly sheep, which threatens the production of traditional products such as Pirot Kachkaval, Peglana Sausage, and Vurda (Belić et al., 1960; Tomić et al., 2005, 2009, 2011). These trends demonstrate that sustainable land management in southeastern Serbia is closely tied to demographic, particularly in the context of agriculture and the cultural landscape.

Livestock dynamics

Historical livestock data indicate that sheep played a dominant role in the agricultural structure of the Pirot District and Municipality of Pirot (Stevanović et al., 2016a). The predominance of sheep, particularly breeding ewes in the past, reflects the region's long-standing pastoral orientation and represents the historical foundation of its dairy production. Today, the existence of sheep breeding, as well as the Pirot Pramenka breed, is seriously threatened, and substantial reforms are necessary to ensure the survival of sheep farming on Stara Planina.

The occurrence of wild horses, most likely abandoned as a consequence of pronounced depopulation, illustrates the near disappearance of horse breeding on Stara Planina. A comparable decline can be observed across almost all other segments of livestock farming.

The analyses of milk intake and dairy production in the Municipality of Pirot for the period 2019-2024 indicate a gradual decline associated with demographic ageing, climatic variability, and reduced livestock numbers. Overall, the results point to a contraction of the regional milk base. At the same time, traditional cheeses have shown relative resilience, retaining strong market relevance and cultural value, and continue to play an important role in rural sustainability in the Pirot region. Decline in cattle heads definitely endangers future production.

Products and Branding

Based on available natural resources, the area demonstrates potential for the development of diversified agricultural production. However, demographic potential and the existing economic environment represent the main limiting factors for further

development. The long-term prospects for the survival and revitalization of the region are primarily associated with the production of traditional products with geographical indication and the strengthening of the tourism sector. The integration of tourism with sustainable agriculture practices may contribute to a more balanced development model alongside the municipality's established industrial base, led by the Tigar Tire Factory, with potential positive effects on both demographic and economic trends in the Municipality of Pirot. Within this framework, analytical attention is directed toward products that emerged under specific environmental and socio-economic conditions and are produced using traditional methods, including Pirot Kachkaval, Peglana Sausage, and Vurda.

Brief History, Specificity and Significance of Pirot Kachkaval

Pirot Kachkaval, one of Serbia's most renowned traditional cheeses, has been produced for over a century and recognized beyond the Balkans. Rooted in ancient Hellenic, Roman, and monastic cheesemaking traditions, it likely reached the Balkans with Sephardic Jews in the 16th century and spread during the Ottoman period as kaşar, with parallels in Greece (kaseri) and Italy (caciocavallo). Its production was introduced to Stara Planina in the 19th century by Cincar shepherds from Epirus, becoming part of the local pastoral economy (Lazarević, 2021). By 1889, it earned acclaim at the Paris World Exhibition and was exported across the Mediterranean and to the U.S. (Belić et al., 1960). The cheese's distinctiveness lies in the pasta filata process and the mountain flora that shapes its aroma and durability (Satrić et al., 2023). Pirot Kachkaval is protected under the national geographical indication system of the Republic of Serbia, with the current product specification allowing production from cow's milk, although it was traditionally made from sheep's milk (Lazarević, 2021). This remains a cultural and economic emblem of southeastern Serbia, comparable to Parmigiano Reggiano, Manchego, and Roquefort in Europe's cheese heritage.

Peglana Sausage – Branding of a Traditional Meat Product

Pirot *Peglana* sausage is a traditional meat product of Eastern Serbia, closely associated with the Pirot region. It is neither smoked nor treated with additives but is manually pressed during the ripening process, which results in a specific texture and extended shelf life (Tasić et al., 2019). Nutritional analyses indicate a high protein and fat content, a predominance of saturated fatty acids, and the absence of nitrites, contributing to product safety and quality (Tasić & Pavlović, 2023). The product is protected under the national geographical indication system of the Republic of Serbia, which establishes its legal association with the local area and production specifications (Stevanović et al., 2016b). Beyond its physical and nutritional characteristics, *Peglana* sausage reflects regional food heritage and illustrates how traditional production methods and specific environmental conditions can contribute to value creation, tourism potential, and the preservation of cultural heritage.

Vurda – Traditional Soft Cheese and Regional Branding

Pirot Vurda is a traditional dairy product of southeastern Serbia, obtained through the natural draining of sheep's, cow's, or mixed milk, resulting in a soft, mildly acidic spread. Since 2023, Lužnica Vurda has held PGI protection and its products are made from Simmental milk in the Lužnica Valley under defined technological parameters, including fat content, salt concentration, and pH, with a seven-day ripening period at 20–30 °C (ZIS, 2023). Beyond its sensory quality, it symbolises authenticity and local identity, supporting rural branding and tourism (Urošević et al., 2018). Together with Pirot Kachkaval and white cheese, Vurda reflects the environmental conditions and pasture-based livestock systems of the Stara Planina area (Tomić et al., 2011; Ružić-Mušlić et al., 2011). The Dairy School "Dr Obren Pejić" continues to preserve these traditions and support geographical-indication protection, contributing to the long-term cultural and economic sustainability of the region (Stojsavljević et al., 2015; Albaladejo-García et al., 2024).

Comparative Analysis of Pirot Kachkaval and Selected World Cheeses

Pirot Kachkaval, a traditional sheep's milk *pasta filata* cheese, from southeastern Serbia, is produced by manual curd stretching and ripened for approximately 60 days, which results in a firm texture and mildly acidic flavour (Satrić et al., 2023). From a technological perspective, it shows similarities to Italian Caciocavallo but retains a distinct regional identity shaped by Stara Planina's pastures and microclimate (United States Department of Agriculture [USDA], 1978). When compared with long-aged European cheeses such as Parmigiano Reggiano and Grana Padano (9-36 months) or PDO-protected varieties like Manchego, Feta, and Roquefort, Pirot Kachkaval, with partial PDO status for cow's milk, stands out for its authenticity and cultural significance (FAO, 2013; Chandan, 2014; Fox et al., 2017; Tridge, 2025). Despite its shorter ripening, it remains a key emblem of Serbian pastoral and gastronomic heritage, aligned with Europe's tradition of geographically protected artisanal cheeses.

Conclusions

This study confirms that the Municipality of Pirot, despite severe demographic decline and pressures on land use, retains notable resilience rooted in natural resources, cultural heritage, and traditional production. Analyses of demographic and CORINE data clearly reveal structural weaknesses, particularly in mountain settlements, where the level of depopulation is so high that revitalization will not be possible without strong, targeted measures.

Practical recommendations for sustainable development should focus on an integrated approach:

1. Tourism and gastronomy can link rural food production with tourism potential and stimulate demographic and economic recovery. For example, mountain villages could become centres for gastronomic and eco-tourism, including tastings of

traditional products such as Pirot Kachkaval, Peglana Sausage, and Vurda. Abandoned buildings could be adapted into hubs for digital nomads or small tourist accommodations, thereby stimulating the local economy and reviving settlement.

2. Village specialisation, given the different capacities of lowland and mountain settlements, individual villages could develop specialised roles:

- Tourist-gastronomic (e.g., tasting centres, traditional craft workshops),
- Rural-agricultural and livestock (maintaining and valorising indigenous breeds and traditional products),
- Multifunctional, combining accommodation, tourism, and local production.

3. Support through subsidies and institutional measures - development potential can be significantly enhanced via national and European subsidies, including financial assistance for livestock preservation, modernisation of processing facilities, certification of geographically indicated products, and support for agrotourism projects.

4. Realistic approach to repopulation - given the extreme depopulation of higher-altitude villages, the goal should not be mass return, but gradual creation of sustainable, multifunctional communities. Selective attraction of young families, entrepreneurs, and professionals (e.g., digital nomads, agro-tourism operators) combined with economic opportunities, infrastructure, and local services will foster incremental revitalisation rather than an unrealistic demographic turnaround.

In conclusion, sustainable development in the Municipality of Pirot depends on a combination of demographic renewal, responsible land management, and strategic valorisation of traditional products, with a particular emphasis on tourism and gastronomy as key drivers of revitalisation and socio-economic resilience in mountain communities. A realistic, phased approach that focuses on creating viable, specialised communities is essential for long-term success.

The findings of this study should be interpreted in light of certain limitations. The analysis is based on a single case study at the municipal level and relies primarily on aggregated demographic, land-use, and agricultural statistics, which may limit the ability to capture finer-scale socio-economic processes. CORINE Land Cover data for the Pirot Municipality are limited by their 25 ha minimum mapping unit, generalization of complex landscapes, 6-year update intervals, difficulty capturing small or steep areas, and potential misclassification of transitional vegetation and post-fire sites.

Future research could build on these findings by expanding the spatial scope of analysis to include comparative studies of other rural and mountain municipalities, as well as by integrating more detailed farm-level and qualitative data. Such approaches would contribute to a deeper understanding of local development dynamics and provide a stronger basis for designing targeted rural development policies.

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Conflict of interest

The authors declare no conflict of interest.

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Example:

Table 1. The distribution cost of packaged goods from Subotica to retail-store objects

Indicators	Period			Total
	Month 1	Month 2	Month 3	
Distance crossed (km)	12.926	11.295	13.208	37.429
Fuel consumption (litre)	3.231	2.823	3.302	9.356
Value of fuel consumption (RSD)	242.378	211.790	247.653	701.821
Total time spend on touring (hour)	314	266	417	997
Value of total time spend on touring (RSD)	47.048	39.890	62.570	149.508
Number of tours	98	77	102	277
Toll value (RSD)	0	0	0	0
Number of pallets transported (piece)	1.179	976	1358	3.513
Total weight transported (kg)	602.600	429.225	711.116	1.742.941
Vehicle maintenance costs (RSD)	203.858	164.970	224.806	593.634
Lease costs (RSD)	480.938	454.214	565.784	1.500.936
Total sum (RSD)	974.222	870.864	1.100.813	2.945.899

Source: Petrović, 2012

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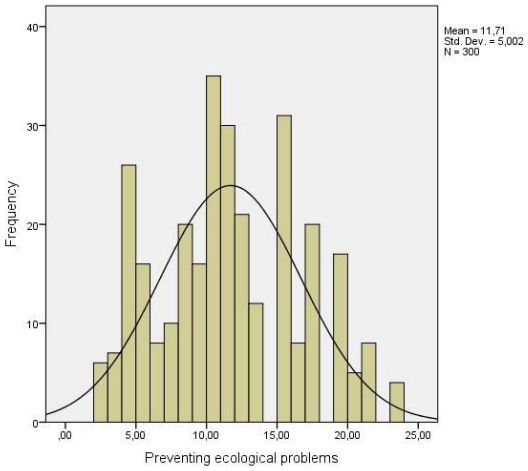
Figure 1. Agriculture, value added (% of GDP)



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