



Adoption and Impact of Agricultural Innovations on Farm Productivity and Sustainability in North Macedonia

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Abstract

Agriculture is undergoing a profound transformation driven by rapid advances in digital technologies, biotechnology, automation, and sustainable production practices. This paper examines the key innovations reshaping modern agriculture and evaluates their technological, economic, and environmental impacts. Precision farming tools—such as drones, sensor networks, and GPS-guided machinery—are improving resource efficiency and enabling data-driven decision-making. Artificial intelligence and big data analytics further enhance predictive capabilities in crop management, pest control, and yield forecasting. Breakthroughs in biotechnology, including gene editing and advanced breeding techniques, contribute to the development of resilient, high-quality crop varieties suited to climate challenges. At the same time, automation and robotics are reducing labor constraints and increasing operational efficiency across agricultural systems. Digital supply-chain platforms and traceability technologies strengthen market transparency and support more competitive and sustainable food systems. While these innovations offer substantial benefits for productivity and sustainability, their adoption is influenced by factors such as cost, infrastructure, and farmer knowledge. The paper concludes that strategic investment, targeted training, and supportive policy frameworks are essential for unlocking the full potential of innovation-driven agricultural development.

Keywords: Agricultural innovation, Precision farming, Sustainable agriculture, Smart agriculture, Digital transformation

Introduction

Agriculture, one of the oldest and most essential human activities, is experiencing an unprecedented era of technological transformation. Over the past decade, rapid advances in digital technologies, biotechnology, automation, and data science have reshaped the foundations of agricultural production and management. These innovations are emerging as vital responses to the complex challenges facing the global food system, including climate change, resource scarcity, market volatility, labor shortages, and the growing demand for high-quality and sustainable food products. As a result, modern agriculture is increasingly shifting from traditional, experience-based practices to more precise, data-driven, and technologically integrated production systems.

Key to this transformation is the rise of smart and precision agriculture, which integrates sensor technologies, drones, satellite tracking, Internet of Things (IoT) applications, and GPS-guided machinery. These tools allow farmers to collect real-time data on soil conditions, plant health, and environmental factors, enabling targeted application of inputs and more efficient use of resources. Equally important is the accelerated adoption of artificial intelligence (AI) and big data analytics, which support predictive modeling, early detection of pests and diseases, automated decision-making, and optimization of production processes. Such technologies not only increase productivity but also reduce uncertainty in agricultural operations.

The growing implementation of automation and robotics - including autonomous tractors, robotic harvesters, and automated irrigation systems - is addressing labor shortages and improving the efficiency and consistency of agricultural operations.

Beyond production, digital innovations are transforming agricultural value chains through the integration of blockchain systems, digital marketplaces, and traceability technologies. These tools improve supply chain transparency, strengthen food security and create new opportunities for market competitiveness.

Despite the clear benefits of these innovations, their adoption is uneven across countries and farm sizes, often constrained by high initial costs, lack of technical knowledge and insufficient infrastructure. Understanding the dynamics, impacts and barriers associated with agricultural innovation is therefore crucial for policymakers, researchers and practitioners working to foster sustainable agricultural development.

This paper explores the most significant technological advances that are transforming modern agriculture and analyses their implications for productivity, sustainability and economic performance. By examining current trends and emerging technologies, the study provides insights into how innovations can shape the future of agriculture and contribute to more resilient and efficient food systems.

Material and Method

This study employed a survey-based research design aimed at gathering relevant data from agricultural producers in the municipality of Prilep, Republic of North Macedonia. A structured questionnaire was developed to examine farmers' experiences, perceptions, and levels of adoption of modern agricultural innovations. The instrument included multiple-choice questions, and open-ended questions to ensure comprehensive coverage of both quantitative indicators and qualitative insights.

The sample consisted of 30 individual farmers, selected based on their active involvement in agricultural production. All selected participants completed the questionnaire, resulting in a 100% response rate, which ensured the reliability and representativeness of the findings at the local level. The survey was administered through face-to-face visits, enabling the researchers to clarify questions when necessary and improve the accuracy of responses.

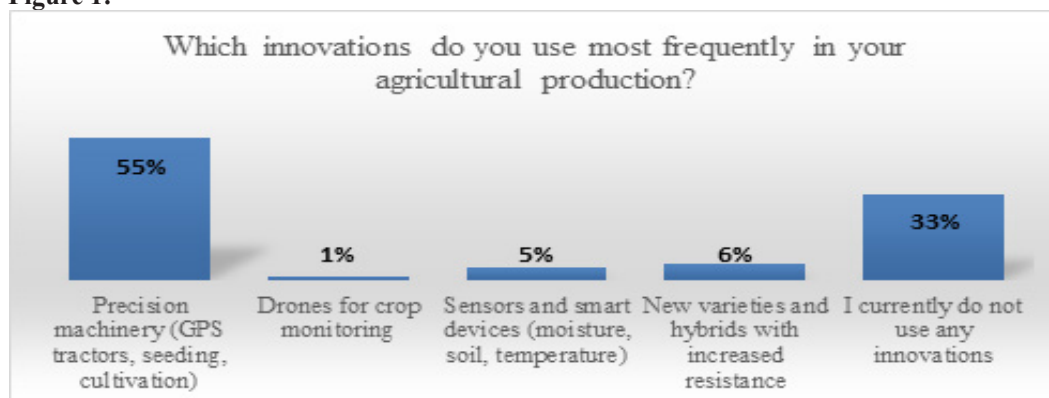
After the data collection phase, all quantitative responses were entered and analyzed using Microsoft Excel, allowing for the generation of descriptive statistics such as frequencies, percentages, and comparative tables. Qualitative answers were reviewed, coded, and thematically grouped in order to identify recurrent perspectives, challenges, and opportunities perceived by farmers regarding innovation in agriculture.

The processed data form the basis for the analysis presented in the following sections, offering insights into the current state of technological transformation and innovation adoption among farmers in the Prilep region.

Results and Discussions

The results obtained from the conducted survey provide a clear insight into the current level of innovation adoption among farmers in the Prilep region. The collected data reveal significant differences in the use of modern technologies, as well as in farmers' readiness and capacity to integrate new solutions into their production processes. Through the analysis of the responses, several key patterns emerge regarding the types of innovations being adopted, the barriers that limit their implementation, and farmers' perceptions of their impact on productivity and future investment decisions. The following sections present a detailed interpretation of these findings and discuss their broader implications for advancing agricultural modernization at the regional level.

Figure 1:



Analysis of the responses collected shows (Figure 1) that farmers most often rely on innovations related to precision machinery, which are used by 55% of respondents. This high level of adoption indicates that technologies such as GPS-guided tractors, precision seeding and modern cultivation tools are perceived as practical, reliable and immediately useful for improving efficiency and reducing resource use. These technologies often represent an entry point into the modernization of agriculture, as they are closest to traditional practices and require minimal changes to existing work processes.

At the same time, a significant proportion of farmers - 33% - stated that they are currently not using any innovations in their agricultural activities. This finding highlights a marked heterogeneity in the level of modernization and shows that one third of producers continue to rely entirely on traditional production systems. The reasons may stem from financial constraints, insufficient knowledge, lack of confidence in new technologies or the perception that adopting innovations is complex and risky. This group represents a critical target for future training programs, advisory services, and support measures.

The use of new varieties and hybrids with increased resistance is also limited, with only 6% of respondents implementing such solutions. While these innovations are among the most accessible and cost-effective ways to address climate and biological stresses, their limited adoption suggests that farmers may lack information, have reservations about the performance of new

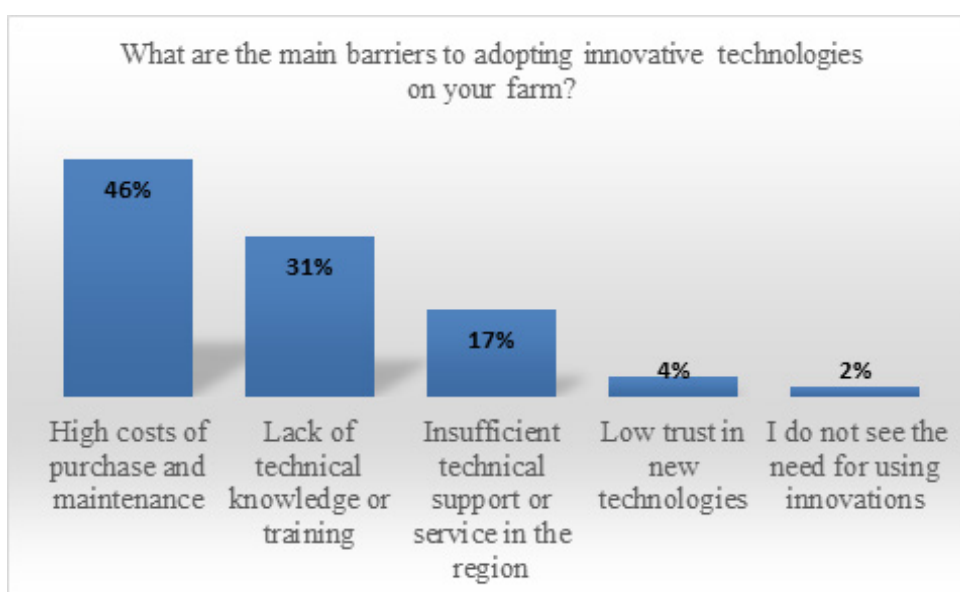
genetic materials, or have limited access to high-quality planting material. This further highlights the need for demonstration fields and stronger advisory support.

Similarly, only 5% of farmers surveyed use sensors and smart devices to monitor soil conditions, moisture, or temperature, indicating that digitalization in agriculture in the region remains at a very early stage. Potential barriers include high initial investment costs, insufficient technical support, and weak digital infrastructure. Although such technologies offer significant opportunities for optimizing resource management, they remain much less widely adopted compared to mechanical innovations.

The use of drones is even more limited, with only 1% of farmers using them for crop monitoring. This extremely low percentage suggests that high-tech solutions are rarely adopted, probably due to high costs, a lack of trained operators, and limited awareness of the benefits that drones offer, such as early disease detection, crop health monitoring, and timely identification of production risks.

It can be seen that the modernization of agriculture in the region is progressing gradually - starting with mechanization and practical technical solutions, while digital and biotechnological innovations still show very low adoption rates. This creates a clear basis for designing targeted measures that can encourage the integration of advanced technologies through education, demonstration activities, and institutional support.

Figure 2:



Source: author's research

The responses clearly highlight that financial constraints are the most significant obstacle preventing farmers from adopting innovative technologies (Figure 2). A total of 46% of the respondents pointed to the high costs of purchasing and maintaining modern equipment as the primary barrier. This indicates that even when farmers recognize the potential benefits of innovation, the initial investment required for advanced machinery, sensors, drones, or digital tools remains beyond the financial reach of many producers. Such a pattern is common in regions with small and medium-sized farms, where budgets are limited and long-term return on investment is uncertain. High costs therefore act as a decisive deterrent, slowing down the transition toward modern, technology-driven agriculture.

The second major barrier, reported by 31% of respondents, is the lack of technical knowledge or training. This finding demonstrates that innovation adoption does not depend solely on financial capability but also on the availability of skills and confidence to operate new systems. Many farmers still feel unprepared to integrate digital tools, interpret sensor data, or use advanced machinery without formal training. This situation suggests that the adoption of innovations requires structured educational programs, practical demonstrations, and regular advisory support that can bridge the knowledge gap and reduce uncertainty among producers.

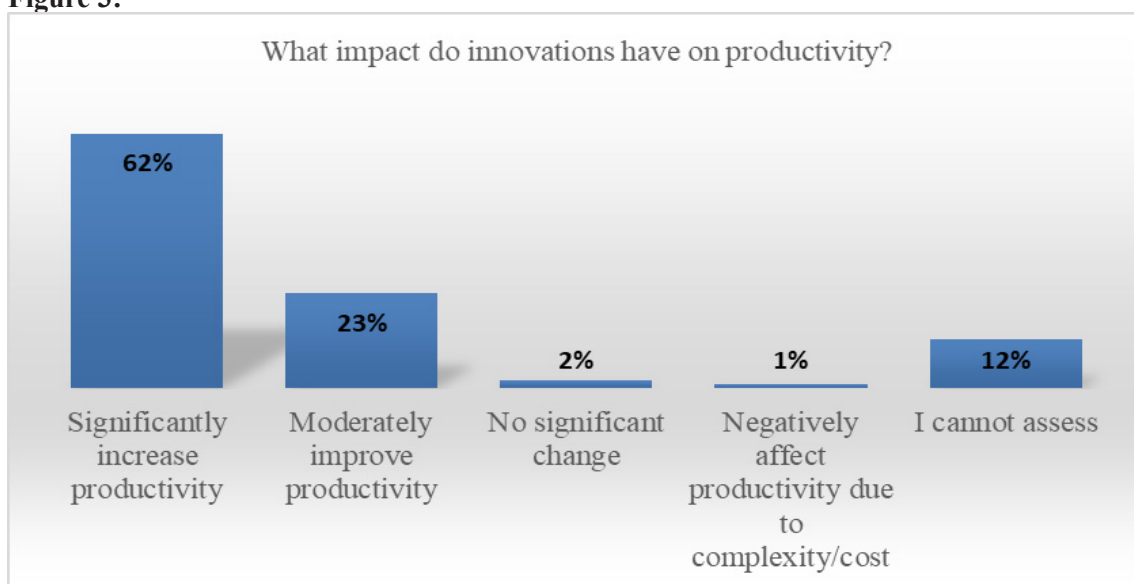
In addition, 17% of the surveyed farmers believe that insufficient technical support or service availability in the region further limits their ability to implement innovations. Even those willing

to invest in new technologies may hesitate if there are no local technicians to provide maintenance, repairs, or troubleshooting. This challenge emphasizes the importance of building regional infrastructure and service networks that can sustain the use of technology over time. Without such support, innovations are perceived as risky, especially in environments where downtime during the production season can lead to significant losses.

Other barriers play a noticeably smaller role. Only 4% of farmers expressed low trust in new technologies, suggesting that skepticism exists but is not a dominant factor. This percentage indicates that the majority of farmers are not resistant to change out of principle; instead, they are primarily constrained by practical limitations such as cost and knowledge. An even smaller share, just 2%, stated that they do not see the need for using innovations at all. This shows that the concept of technological advancement is widely accepted, and only a small minority remains unconvinced of its relevance to agricultural productivity and sustainability.

The adoption of innovative technologies is hindered far more by structural and economic limitations than by attitudinal resistance. Farmers generally acknowledge the value of innovation, but the combination of high costs, insufficient training, and limited regional support creates a challenging environment for technological progress. Addressing these barriers through targeted subsidies, accessible training programs, and improved technical infrastructure would significantly accelerate the modernization of agricultural production in the region.

Figure 3:



Source: author's research

The survey results (Figure 3) clearly show that farmers overwhelmingly consider innovation to have a positive impact on productivity. The majority, representing 62% of respondents, stated that innovation significantly increases productivity. This strong consensus reflects a high level of awareness among producers about the benefits of modern technologies, especially in terms of improved efficiency, reduced manual labor and more precise management of production processes. Farmers who are already implementing innovations – especially precision machinery and improved varieties – appear to be directly experiencing measurable benefits, which strengthens their confidence in continued technological adoption.

A significant proportion of respondents, representing 23%, believe that innovation moderately improves productivity. This group likely includes farmers who have only adopted certain technologies or are using them in a limited capacity. Their experience shows that while innovations can lead to improvements, the effects can vary depending on the size of the farm, the type of crop, the availability of resources or the specific technologies used. This response highlights that productivity gains are not uniform across farms and may depend on the extent to which innovations are integrated into the overall production system.

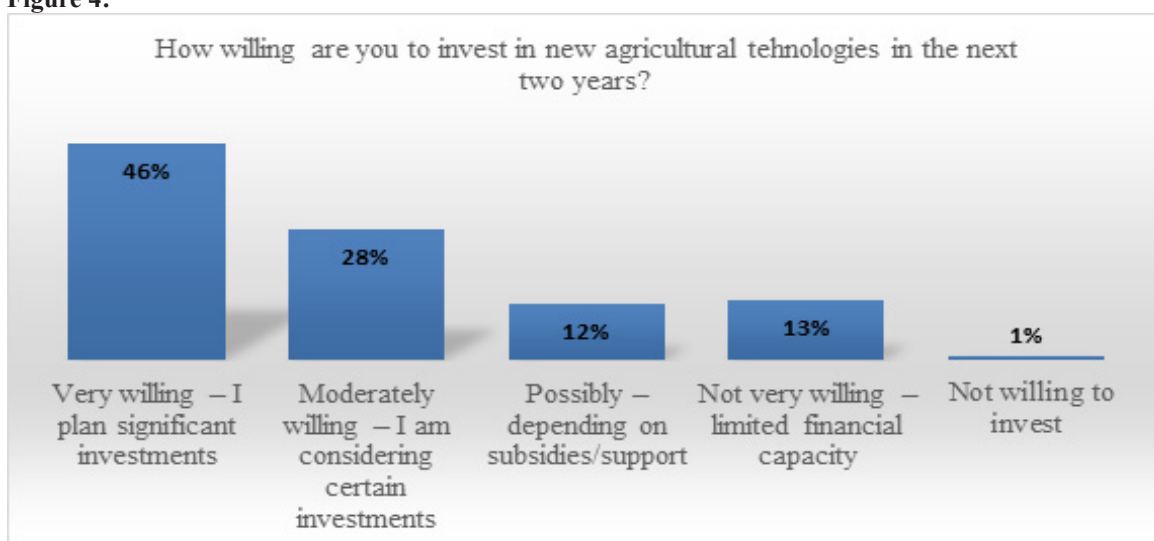
Only a very small percentage of farmers reported neutral or negative experiences. Only 2% stated that innovations did not bring about a significant change in productivity. Such responses may come from farmers who have introduced minimal technological adjustments or who operate in production systems where short-term results are difficult to observe. Similarly, only

1% believe that innovations negatively impact productivity, most likely due to the perceived complexity of new tools, increased maintenance requirements, or additional costs associated with their operation. These farmers may have faced challenges related to improper implementation, lack of technical support, or insufficient training, which may temporarily hinder productivity rather than increase it.

An additional 12% of respondents stated that they were unable to assess the impact of innovations. This uncertainty is likely related to limited exposure to modern technologies or incomplete information about their long-term effects. It may also reflect situations in which farmers have recently adopted new tools and have not yet had the opportunity to assess their full impact on yields or efficiency. Their hesitation highlights the importance of continued demonstration activities, farmer field schools, and advisory services that can provide clear, evidence-based insights into the benefits of innovations.

The results show a strong and predominantly positive perception of the role of innovation in increasing productivity. Most farmers acknowledge that technological improvements are closely linked to higher yields, better resource management, and greater operational efficiency. The small proportion of negative or uncertain responses suggests that the primary challenges lie not in the concept of innovation itself, but in access, training, and practical implementation. These findings reinforce the broader conclusion that expanding the adoption of innovations-supported by education, financial incentives, and technical assistance-has significant potential for improving agricultural productivity at the regional level.

Figure 4:



Source: author's research

Figure 4 indicates a generally strong openness among farmers to invest in new agricultural technologies in the next two years. The majority of respondents, representing 46%, stated that they are very ready and are already planning significant investments. This high percentage shows a clear trend towards modernization and reflects the growing understanding among farmers that technological progress is essential for improving productivity, competitiveness and long-term sustainability. These farmers seem confident in the benefits of innovation and probably belong to a group that is already familiar with precision machinery or other modern solutions, which increases their readiness for further upgrades.

Another significant share, 28%, stated that they are moderately ready, indicating that they are considering specific investments, but may still be evaluating costs, yields or the most appropriate technologies for their farm structure. This group reflects a cautious but positive attitude, where farmers recognize the importance of technological progress, but are cautious in making decisions. Their willingness suggests that with clearer information, practical demonstrations or supportive policies, their investment intentions could easily be strengthened.

An additional 12% stated that they would consider investing depending on the availability of subsidies or government support. This response illustrates the crucial role of institutional support in enabling technology adoption. For these farmers, investments are not determined by reluctance, but by economic constraints. Subsidies, grants or favorable credit programs would therefore act as decisive incentives, highlighting the importance of public support mechanisms in accelerating regional agricultural modernization.

In contrast, 13% of respondents stated that they were not very willing to invest due to limited financial capacity. This group highlights the persistent economic barriers that prevent farmers from engaging in technological transformation, even when they understand its potential benefits. Their reluctance is based primarily on financial insecurity, not on resistance to innovation itself. Addressing this challenge requires targeted financial instruments, risk-sharing programs, and accessible credit structures tailored to small and medium-sized farms.

Only 1% of respondents stated that they would not be willing to invest under any circumstances. This remarkably low percentage indicates that resistance to innovation as a concept is almost non-

existent among the farmers surveyed. Overall, the data reveals a community that is largely future-oriented, motivated to adopt modern technologies, and aware of their importance for future growth. The main constraints are financial, not attitudinal.

Collectively, these results indicate a favorable environment for advancing agricultural innovation in the region. With appropriate financial support, advisory services, and continued promotion of technological benefits, it is very likely that the already strong willingness to invest will translate into concrete modernization on a significant portion of farms in the next two years.

Based on the findings analyzed, the results clearly indicate that the adoption of modern agricultural innovations in the region is increasing, but is still constrained by economic, technical and educational constraints. It is seen that farmers who implement advanced technologies achieve greater efficiency and better resource management, reinforcing the importance of innovations for sustainable growth. At the same time, the identified challenges highlight the need for stronger institutional support, improved training and greater access to financial instruments. These insights provide an important basis for the development of future policies and strategies aimed at advancing modern agricultural production.

Conclusion

This study provides a comprehensive assessment of the current level of innovation adoption among farmers in the Prilep region and offers insights into the factors shaping the modernization of agricultural practices. Empirical evidence shows that technological progress in the sector is progressing, albeit unevenly, and is strongly influenced by farmers' financial capacity, access to knowledge, and exposure to institutional support. The results confirm that the adoption of modern technologies – ranging from advanced mechanization to elements of digital and precision agriculture – contributes to measurable improvements in production efficiency, resource optimization, and overall management performance.

Despite these positive developments, several structural constraints continue to hinder wider adoption. High investment costs, limited access to favorable credit instruments, and uncertainty regarding the economic returns of new technologies remain significant obstacles. Equally critical are gaps in technical competencies and the insufficient availability of targeted training programs that would facilitate the efficient and reliable

use of innovative tools. These findings confirm that technology adoption in agriculture is not only dependent on the availability of equipment, but is embedded in a broader socio-economic and institutional context.

However, a clear and growing awareness among farmers is identified regarding the strategic importance of innovation for maintaining competitiveness and ensuring long-term sustainability. Respondents who have integrated modern practices into their production systems report improvements in operational precision, cost efficiency, and resilience to market and environmental pressures. Such results highlight the potential of innovation not only to increase productivity, but also to strengthen the adaptability of the agricultural sector.

The evidence presented highlights the need for a more coherent and integrated policy framework aimed at accelerating the modernization process. Priority measures should include expanding financial support mechanisms, strengthening agricultural extension services, and improving access to practical and continuous training. In addition, fostering collaboration between research institutions, policymakers, and the agricultural community will be essential to ensure that innovation efforts are aligned with real production needs and regional development priorities.

The study finds that while significant progress has been made, significant opportunities remain to further advance the technological transformation of agriculture in the region. By addressing the identified constraints and strengthening systemic support structures, agriculture can more effectively transition to a model characterized by efficiency, sustainability, and innovation-driven growth.

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